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Sediment budget Of the Shoalhaven coastal compartment

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SEDIMENT BUDGET

OF THE

SHOALHAVEN COASTAL COMPARTMENT

By

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Declaration

I, Rafael Carvalho, declare that this thesis, submitted in fulfillment of the requirements for the award of Doctor of Philosophy, in the School of Earth and Environmental Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Abstract

This study investigates coastal processes using a sediment budget approach based on the concept of conservation of mass at a decadal time scale. Assessments of the sedimentary characteristics, contributions (sources), losses (sinks), and transport pathways were conducted for the Shoalhaven coastal compartment, a secondary level compartment defined by Geoscience Australia, that stretches for 32 km of coastline in southeastern Australia and that shows no evidence of sediment contributions from the south nor losses towards the north.

The Shoalhaven coastal compartment is composed of three tertiary level compartments. The embayment of Seven Mile Beach-Comerong Island is the northernmost, Culburra Beach is the middle one, and the embayment encompassing Warrain and Currarong Beach forms the southernmost. Sediment exchange between these compartments is believed to be negligible, due to the headlands of Crookhaven Heads and Penguin Head and the adjacent underwater reefs.

The Shoalhaven River, the main source of sediments to the Shoalhaven coastal compartment, intermittently discharges sediments to the nearshore of the northernmost tertiary level compartment. The river drains a temperate catchment of 7,151 km^2 with average annual rainfall of 900 mm and crosses the Palaeozoic Lachlan Fold Belt in the upper-middle section and the southern Sydney Basin in its lower section. Lake Yarrunga, the reservoir formed as a result of the construction of Tallowa Dam in 1976, has smoothed the flash flooding of the river considerably, and trapped most of its fluvial sediment load. Based on deposition in the reservoir between 2003 and 2014 and its trapping efficiency of 88 %, it was estimated that an average of approximately 86,000 m^3/y is delivered from the catchment to the estuary.

The Shoalhaven barrier estuary is in a mature state of infill. The complex pattern of surficial sediments of the Shoalhaven estuary reflects the modification of its natural course artificially diverted to exit at Crookhaven Heads, after the construction of Berrys Canal in 1822. The former mouth of the river at Shoalhaven Heads has been impounded by the deposition of a sandy berm. In the past 65 years, the beach berm has been breached temporarily eight times following major floods, with the gradual re-establishment of the berm, taking less than nine months after recent events. The estuary experienced accretion of at least 1,020,000 m^3 of sediments between 1981 and 2006,

despite the widespread erosion observed especially downstream of Berrys Canal. In the same period, the estimated sediment contribution from the catchment was 2,150,000 m^3, whereas the volume of material discharged to the nearshore was 1,065,000 m^3.

The estimated sediment delivered to the nearshore and the observed volumetric change experienced at Seven Mile Beach-Comerong Island between 1972 and 2013 were used to calculate the sediment budget of the northernmost compartment. A beach accretion of approximately 2,680,000 m^3 was estimated based on shoreline displacement in the 41-year period. A residual of 1,615,000 m^3 was obtained when compared to the estimated nearshore deposition between 1981 and 2006. It is suggested that the bulk of this residual was possibly provided by a combination of factors that includes: i) the unknown volume added to the nearshore before 1981; ii) more sediments deposited in the nearshore following breaching events between 1981 and 2006; iii) the transport of sands from the nearshore deposit to the beach after 2006; and/or iv) a shoreface supply of sediments to the beach.

Culburra Beach received no sediment from fluvial sources and the beach accreted approximately 240,000 m^3 between 1972 and 2013. It is estimated that most of the contributions derived from *in situ* carbonate-secreting organisms and a limited shoreface supply of sand to the beach.

A volume of approximately 1,500,000 m^3 was obtained using the shoreline displacement approach during the same time interval for the Warrain-Currarong Beach tertiary level compartment, although it appears to have been over-estimated. The southernmost compartment received negligible fluvial sediments from Coonemia Creek and possibly low volumes from Currarong Creek. Landforms at the entrance of Lake Wollumboola, a shallow saline coastal lagoon, suggests that the lake is a major sink of marine sediments for this compartment. As in the case of Culburra, it is inferred that most of the contributions derived from *in situ* carbonate-secreting organisms and a limited shoreface supply.

Several assumptions and uncertainties constrain the final coastal budget, but this study provides the framework for future research, offering a broad view of the coastal area by organizing what is known and identifying where gaps in understanding exist. It also provides an avenue for management action using not only the results presented in this study but also enabling further modelling to explore scenarios of erosion or accretion in response to natural events or engineering interventions in the area.

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The accomplishment of this thesis would not be possible without the assistance of many people. First I would like to thank Prof. Colin Woodroffe for the facilitation, assistance, supervision, friendship and enthusiasm throughout this study.

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Chapter 1: Introduction

The coastal zone is one of the most dynamic parts of the Earth, a highly changeable interface between land, sea and atmosphere, which encompasses a variety of complex systems and landforms that are used extensively for a large number of activities and are evolving over varying time scales. The shoreline, the coastal boundary layer between the Earth's systems, is rarely static as it responds to the major processes acting upon it and in turn, modifies those processes in a mutual co-adjustment of form and process known as coastal morphodynamics (Wright and Thom, 1977, Cowell and Thom, 1994). Coastal morphodynamics are primary controlled by the movement of sediments as a result of a range of processes that are likely to be acting simultaneously or in sequence, reshaping the coastal landforms (Woodroffe, 2003).

Morphodynamic studies of the NSW coast have provided a framework for understanding long-term (decades or longer) coastal evolution and the shorter term (seconds to seasons) patterns of erosion. After the destructive effects of storms in 1967, 1972 and 1974, there has been increased awareness of the importance of management of the coast in NSW (Chapman et al., 1982). Coastal erosion is the result of an excess of sediment removal over supply within a specified coastal segment, such as a sandy beach, and over a specified time period. The beach is merely the active and visible part of the shoreface, which extents well seawards of the beach. Changes within this zone can be framed in terms of a coastal sediment budget. The natural beach exhibits short-term fluctuations within dynamic equilibrium (Chorley and Kennedy, 1971), whereas over hundreds of years a particular coastal area may be slowly eroding or accreting (Chapman et al., 1982).

Sediment budgets are a fundamental element of coastal sediment process studies (Komar, 1998) in geomorphology and engineering through application of the primary conservation of mass equation (Rosati, 2005). The sediment budget concept involves understanding the sediment sources, sinks, and transports for a selected part of the coast, within a period of time. A budget can be developed to represent short (seasonal or annual changes) or long-term (decadal) conditions commonly required to represent periods of geomorphic and engineering significance (Rosati and Kraus, 1999, Patsch and Griggs, 2006). The sediment budget is a balance of volumes of sediments and determines whether the shoreline will prograde, remain stable or erode, providing useful insight into the management of coastal compartments (Komar, 1996)

The term was first introduced in Australia by Davies (1974), whose actual idea is based on the concept of littoral cells presented at the International Geological Congress in Copenhagen by Inman and Chamberlain (1960), after observations that part of the California coast was naturally divided into discrete sedimentation cells by the configuration of coastal drainage basins, headlands and shelf bathymetry (Inman, 2003). In the UK, mapping of major regional littoral drift cells and sub-cells based on the interruptions to the movement of sand or shingle along the beaches or nearshore seabed (Motyka and Brampton, 1993) provided the basis for shoreline management plans for England and Wales (Cooper et al., 2002, Nicholls et al., 2013). As indicated above, no consensus exists in the terminology available in the literature and several slighty different expressions in meaning to coastal compartments, including littoral cells, sediment cells, coastal cells and coastal sectors, are frequently used (Stul et al., 2012, Woodroffe et al., 2012, Eliot, 2013).

In this thesis, a coastal compartment is considered a component of the geological framework of the coast (McPherson et al., 2015), a subdivision of the coastal zone for management and planning purpose based on sediment flows and landforms that occupies a threefold hierarchy of scales (Thom, 2014). The primary level is based on the influence of large-scale landforms and offshore processes; the secondary level on medium-scale landforms and regional sediment processes and the tertiary level is based on individual beaches (Thom, 2014). Coastal compartments also have a landward and seaward boundary according to the scale of analysis, and compartmentalisation identifies boundaries within which to consider the implications of engineering works and management strategies especially at state and local government levels to reduce risks and protect coastal assets and values.

The general concept of the sediment budget approach was mainly pioneered by Bowen and Inman (1966) in an application along the nearly straight beaches in the vicinity of Point Arguello, on the Californian Coast, following previous works on sediment mineralogy (Trask, 1952), beach profiles (Trask, 1955), sand entrapment rates (Johnson, 1952, 1959), among others. After being pioneered in the western USA, sediment budgets have been developed for a variety of coastal settings around the world, including the barrier islands of eastern USA (Pierce, 1969, Inman and Dolan, 1989, Rosati, 2005), the pocket beaches of Japan (Sunamura and Horikawa, 1977), the cliffs, mudflats and saltmarshes (Bray et al., 1995) and estuaries (Townend and Whitehead, 2003, French et al., 2016) of the UK, and the coastal system of San Francisco Bay, USA (Barnard et al., 2013).

Applications of the sediment budget concept to the Eastern Australian context started in the 1970s with an investigation in the Shoalhaven area in NSW, as well as the Gold Coast in Queensland. The sediment budget of the Shoalhaven Heads area was conducted by DPW (1977), building on initial findings of Wright (1967). DPW (1977) calculated an average contribution from the Shoalhaven River of approximately 100,000 m^3/y, generating a beach progradation estimation of between 0.5 and 1 m/y.

Investigation of the erosion problems on the Gold Coast was conducted by Chapman and Smith (1977) and subsequently by Chapman (1978, 1981). They employed sediment tracers, core sampling, hydrographic and photogrammetric surveys and sediment analyses, and found that the longshore transport dominates at that site at a rate of 180,000-250,000 m^3/y but receives little or no sand from freshly weathered rock, instead sand is derived from erosion of updrift beach ridge systems and sinks are either subaerial or shallow subaqueous.

At Byron Bay, 80 km south of the Gold Coast, the Quaternary geology and offshore sediment budget studies for the region started with Roy and Stephens (1978). This was the same year that Gordon et al. (1978) investigated erosion along the Byron Bay-Hastings Point embayment using a regional sediment budget and predictive model. Gordon et al. (1978) reported the existence of an underlying long-term erosional trend, as a result of the natural imbalance of the sediment budget of the embayment, with much less sand being sourced by longshore transport into the area than out of it, and a loss of material to the offshore region. A regional sediment budget based on shoreline changes, river supply, longshore and cross-shore processes, including beach/barrier system erosion and shelf supply was schematized 35 years later by BMT WBM (2013). Alongside a comparison of historical estimates of average annual net longshore sand transport rates for the region, BMT WBM (2013) included a shoreward sand supply from the inner shelf of approximately 0.5-1 m^3/m/y. This was calculated by Patterson (2013) and used to explain the offset of shoreline recession resulting from the 150,000-550,000 m^3/y of longshore transport gradient in the region.

The PWD (1982a) studied sediment movements and provided a budget for Palm Beach, the most remote of the Sydney metropolitan beaches, by using barrier drilling, longshore transport calculations and aerial photographs. It was estimated an average erosion at ocean beach of approximately 19,000 m^3/y, with 7,000 m^3/y lost through wind transport to the northern dunes and an average of 12,000 m^3/y removed by wave and rip current action carrying sand across the northern boundary of the compartment.

Gordon (1992) presented a coastal process study aimed at halting the recession trend at Kurnell Peninsula, south of Sydney. The study applied bathymetric, seismic and sediment surveys, photogrammetric analyses, calculations of aeolian and surf zone longshore transport, and a sand tracer experiment to conclude that the area is a closed compartment with no substantial losses or gains across its longshore boundaries, and indicated a foreshore recession rate of 51,000 m^3/y, and an aeolian transport induced loss into the transgressive dune of 46,000 m^3/y. The information was later used to develop a management plan, implemented over 14 years, that involved beach nourishment and established a well vegetated foredune, resulting in a "plug" of the pre-existing sink, and therefore, long-term erosion halted.

Sediment budgets have also been inferred with considerations to present day and future climate change scenarios for Avoca Beach, on the NSW Central Coast and Cabarita Beach, on the NSW Far North Coast by Mariani et al. (2013) using both deterministic and probabilistic approaches. The study was undertaken to assess ongoing sediment imbalance and long-term recession due to sea-level rise, considering the longshore and cross-shore transport, biogenic production, and lagoon sequestration, among other processes, and concluded that a probabilistic method was more appropriate for the analysis of the sensitivity of shoreline behaviour to future variability in budget components and to manage the remaining uncertainties and relate them to future shoreline behaviour.

Despite being well documented, as in the Coastal Engineering Research Center-CERC (1984), Komar (1998), Rosati and Kraus (1999) and Patsch and Griggs (2006), the procedure to be followed in constructing a sediment budget is challenging (Woodroffe, 2003) and includes determining the appropriate boundaries of the budget and defining the range and magnitude of sediment transport (contributions and losses), the main challenge recognised by Komar (1998). Once these assessments are made, the net gain or loss should be approximately equivalent to the observed erosion or accretion of a beach and its adjacent environments.

1.1 Study area

The Shoalhaven compartment is located in the temperate microtidal wave-dominated embayed South Coast of NSW. The boundaries for the Shoalhaven coastal compartment in this study follow the subdivisions for primary and secondary level compartments adopted by Geoscience Australia (McPherson et al., 2015). In this context, the Shoalhaven coastal compartment is a secondary level compartment within the much broader primary level Illawarra compartment that extends from Port Hacking to Beecroft Peninsula (Figure 1.1), and whose seaward and landward limits extend to the 130 m isobath (the extent of the continental shelf inundated by sea-level rise following the Last Glacial Maximum) and the 50 m topographic elevation contour (the approximate onshore limit of sediment supply to the coastal zone at the primary level scale – between 1:250,000 and 1:100,000), respectively.

The Shoalhaven coastal compartment occupies a total area of approximately 600 km^2 stretching for 32 km from the sandstone headland of Black Head at Gerroa (north) to the sandstone cliffs of Beecroft Peninsula near Currarong (south). Its seaward boundary is set to the 50 m isobath (depth used to ensure the inclusion of sediment exchanges between the shoreface and the nearshore during storms) and its landward limit (the approximate limit of terrestrial sediment supply at the secondary level scale – between 1:100,000 and 1:25,000) is set to the 25 m topographic elevation contour. The terrestrial area occupies approximately 58 % (350 km^2) of the total compartment area, whereas the marine area comprises 42 % (250 km^2). Submerged rock reefs cover approximately 18 % (46 km^2) of the marine substrate. The relatively narrow passive continental shelf adjacent to Seven Mile Beach-Comerong Island is approximately 32 km wide and breaks around the depth of 130 m (Davies, 1979). A topographic high known as Sir John Young Banks, composed of submarine rocks, extends for 12 km to the northeast of Beecroft Peninsula.

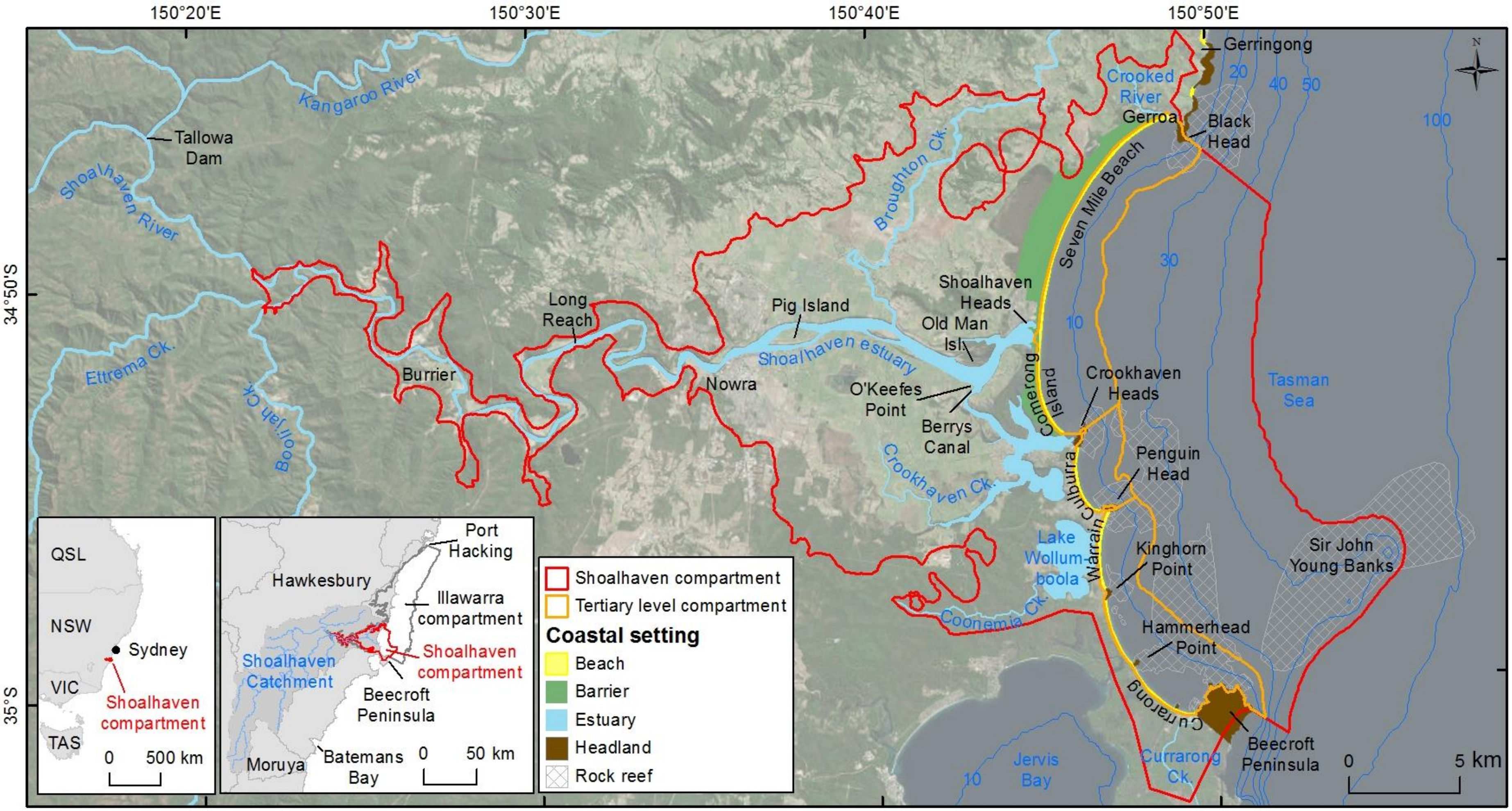


Figure 1.1 Shoalhaven coastal compartment boundaries. Important features such as headlands, beaches and locations are labelled. Bathymetric contours are in meters. Inset maps show compartment location in NSW (left), and on the South Coast of NSW (right) related to the primary level Illawarra compartment, Shoalhaven catchment, adjacent catchments and coastal landforms. Background imagery © LP DAAC.

The Shoalhaven coastal compartment is composed of three tertiary level compartments. The embayment of Seven Mile Beach-Comerong Island is the northernmost, the embayment of Culburra Beach is the middle one, and the embayment encompassing Warrain and Currarong Beach forms the southernmost. The alongshore boundaries between these tertiary level compartments are well defined by the siltstone headlands of Crookhaven Heads and Penguin Head, whereas the 20 m isobath and the back of the foredune (the shore-parallel convex dune ridge formed on the top of the backshore by aeolian sand deposition within vegetation), were used to set the seaward and landward limits. The criteria used in this thesis to set the cross-shore boundaries are based on the seaward limit used by Eliot et al. (2011) in an attempt to include areas subject to variability in response to short-term changes in metocean processes.

The South Coast of NSW is exposed to relatively high south/southeasterly swells, with longshore drift following the main swell direction from southeast to north. Vast quantities of quartzose sand occur on the inner continental shelf between 20 and 70 m depth. Their occurrence is associated with two types of deposits: thin inner shelf sand sheets composed of iron-stained coarser sand grains; and linear shore-parallel 20-30 m thick shelf sand bodies comprising fine-medium grains (Roy and Stephens, 1980, Roy, 2001, Whitehouse, 2007). Past sea-level rose to a maximum of +1.5 m by 7,400 y BP, with the culmination of the Holocene marine transgression followed by sea-level highstand that lasted until approximately 2,000 y BP, before a gradual fall to present level (Sloss et al., 2007).

The mouth of the Shoalhaven River is located 120 km south of Sydney, in the Local Government Area of Shoalhaven City Council. The river is the most important feature associated with this compartment and one of the largest rivers that debouches in NSW waters, draining a catchment area of 7,151 km^2 across the Palaeozoic Lachlan Fold Belt on its headwaters and middle reaches and through the Permo-Triassic sandstones and siltstones of Sydney Basin on its lower section. The river is considered to have supplied sand that contributed to the construction of approximately 40 ridges that nowadays form Seven Mile Beach-Comerong Island, as the shoreline prograded 1,350 m seawards over a period that started around 7,500 y BP according to calibrated radiocarbon dating published in the early 1980s (Thom et al., 1981).

The lower Shoalhaven River is an example of a mature stage estuary, characterised by extensive low-lying Quaternary alluvial plains which have developed as a result of estuarine infill that mostly occurred 5500-3500 radiocarbon years BP (Woodroffe et al., 2000). The natural course of the Shoalhaven estuary has been modified and its flow was artificially diverted to exit at Crookhaven Heads, after the construction by Alexander Berry of a 200-m long canal in 1822 forming Comerong Island (Young et al., 1996, Umitsu et al., 2001). Since then, Berrys Canal continues to widen (Woodroffe et al., 2000) and directs the flow of the Shoalhaven River to exit at Crookhaven Heads. The former mouth of the river at Shoalhaven Heads has been impounded by the deposition of a sandy berm (an inter to supratidal deposited terrace). Following major floods, the outlet is breached temporarily whereas the river flows naturally to the Tasman Sea, with the beach berm gradually re-establishing over time.

Another major alteration in the catchment happened during the construction of Tallowa Dam, upstream of Nowra, in the mid 1970's, and a diversion of the river's water to the Hawkesbury basin in order to augment the water supply of Sydney. This modification has smoothed the flash flooding of the river considerably (Short and Woodroffe, 2009).

Apart from the Shoalhaven River, three other small water bodies discharge into the Shoalhaven compartment. These form the wave-dominated estuary of Crooked River and the intermittently-closed estuaries of Lake Wollumboola and Currarong Creek (Roy et al., 2001). Crooked River has a catchment of approximately 30 km^2 that discharges near Gerroa forming a small barrier estuary (less than 0.5 km^2 in area) in a mature evolutionary stage. Lake Wollumboola is a saline coastal lagoon (Roy et al., 2001) of approximately 6 km^2 that has a similar catchment area to Crooked River (Roper et al., 2010). When the entrance is open, Lake Wollumboola discharges into Warrain Beach.

Currarong Creek has a very small estuary (0.03 km^2) confined by bedrock outcrop and an artificial rock wall. Its entrance is located near Currarong and the catchment drains an area of approximately 12 km^2 (Roper et al., 2011) that extends for 6 km across Beecroft Peninsula (Shoalhaven City Council, 2007).

Possible sediment sources to the Shoalhaven compartment (Figure 1.2) include A) the fluvial supply from the Shoalhaven River, its tributaries and other minor water bodies such as Crooked River, Coonemia and Crookhaven creeks, B) estuarine contributions caused by bank erosion and channel scouring, C) headland contributions due to erosion, D) biogenic *in situ* production of carbonate by calcifying organisms, E) supply of sediments from the shoreface to the beach, and F) updrift supply of sediments from the south towards the Shoalhaven compartment by longshore currents. Possible sediment sinks include: G) deposition of fluvial and marine sediments in the Shoalhaven estuary and Lake Wollumboola, H) sand mining in the Shoalhaven estuary, I) sediment loss from the beach and foredune to the barrier (the shore-parallel landform accumulation of detrital sediments formed by waves, tides and aeolian processes), and J) downdrift loss of sediments from the Shoalhaven compartment by longshore currents towards the north. Besides these contributions and losses to the Shoalhaven compartment, exchanges between: K) estuarine areas and the nearshore, and L) the three tertiary level compartments, would influence the budget of the system.

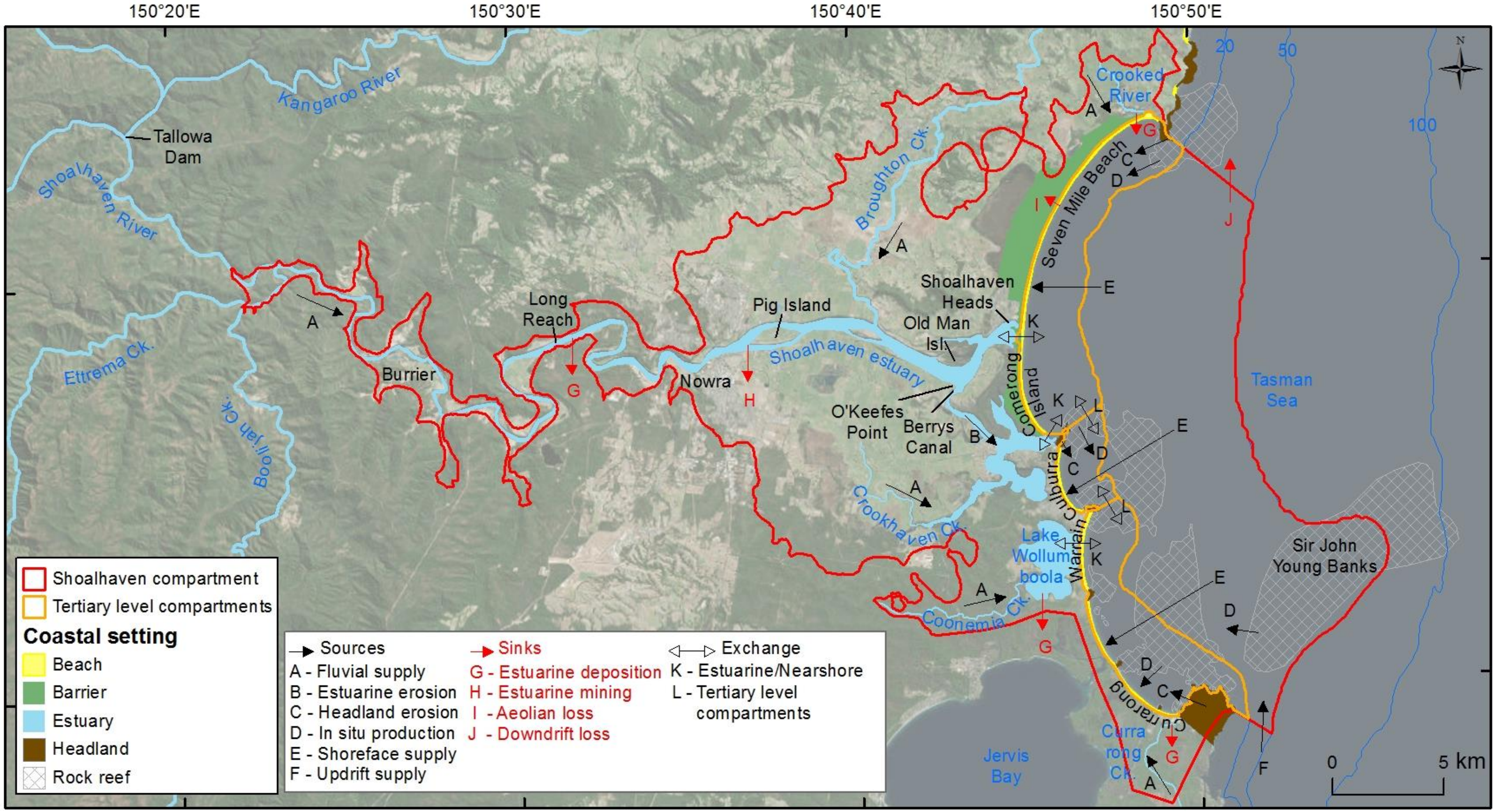


Figure 1.2 The Shoalhaven coastal compartment scheme showing boundaries, sediment sources, sinks and exchange areas from the catchment to the continental shelf. Background imagery © LP DAAC.

1.2 Aims

The main aim of this study is to estimate the sediment budget of the Shoalhaven coastal compartment at a decadal time scale. The approach employed recognises the existence of three tertiary level compartments within the study area and aims to quantify the volume of sediment entering, exiting and the surplus/deficit remaining in each of these compartments. This approach contributes significantly to the available literature on coastal compartments and sediment budgets in Australia, as this study is the first to analyse all tertiary level compartments within the boundaries of a secondary level compartment framework proposed by Geoscience Australia (McPherson et al., 2015). However, due to the importance of the Shoalhaven River, the main feature in the Shoalhaven coastal compartment and the amount of available information associated with it, this study is geographically bias towards the northernmost tertiary level compartment of Seven Mile Beach-Comerong Island.

Specific objectives include: i) to estimate the annual average fluvial sediment yield to the study area; ii) to characterise estuarine, beach and nearshore surficial sediment types; iii) to estimate the volumetric change that occurred to the Shoalhaven estuary and to identify areas of accretion and erosion; iv) to estimate volumetric change based on beach behaviour over short-term and decadal time scales that occurred to the three tertiary level compartments; v) to estimate the volumetric change in the nearshore (the seabed extending from the shoreline to 20 m depth) adjacent to Shoalhaven Heads following breaching events; vi) to investigate the likelihood of alongshore sediment contributions to and losses from the Shoalhaven coastal compartment; and vii) to investigate the likelihood of alongshore sediment exchange of sediments between the three tertiary level compartments.

In order to achieve these aims, sedimentary analyses, coastal characterisation, monitoring and a series of volume calculations using geoprocessing techniques, will be used to answer the questions below:

1.3 Questions

a) What is the sediment yield for the Shoalhaven catchment?

b) What are the characteristics of the surficial sediments and their spatial distribution?
c) Is the Shoalhaven estuary still trapping sediment and how does this vary spatially?
d) Are the beaches that form the three tertiary level compartments behaving in a similar way (eroding, stable or accreting)?
e) How much sediment is delivered to the nearshore and how often?
f) Is the Shoalhaven coastal compartment receiving sediment from the adjacent compartment to the south and/or losing sediment to the north?
g) Is there sediment exchange (bypassing) between the three tertiary level compartments?

1.4 Outline of the thesis

This thesis is composed of seven chapters. The first chapter is a general introduction and contains the objectives and research questions. The second chapter describes the available data and the field, laboratory and analytic methods which have been employed during this research.

Chapters 3 to 6 present the research results and discussion in terms of the different physical settings and environments, in a logical sequence from catchment to nearshore. Chapter 3 describes the fluvial systems and sediment yield to the system. Chapter 4 deals with estuarine processes of sedimentation and estimates the volumetric change that occurred to the Shoalhaven estuary. Chapter 5 characterises the sediments of the beaches, describes processes occurring at the beach-barrier system interface and estimates the beach volumetric change that occurred to the three tertiary level compartments, whereas Chapter 6 comprises the offshore system. This chapter investigates the physical characteristics of the nearshore, the shoreface (the seabed extending from 20 m to 50 m depth) and the volumetric change adjacent to Shoalhaven Heads.

Chapter 7 puts the results of the previous four chapters in the light of a sediment budget for the Shoalhaven coastal compartment and discusses the volumes associated with each individual component of the system, described previously. It also provides a critical discussion of the work completed, comments on the contribution of this project to wider literature, and makes recommendations on potential future research and management.

Chapter 2: Methods

This chapter describes the methods used in the thesis. It is organised into 17 sub-sections that describe the data itself, either collected in the field (primary source) or provided by third parties (secondary source), the laboratory and/or computer methods involved in the processing and analyses, and also the specific usage of these in terms of generated results. Table 2.1 summarises all sub-sections in relation to sources and thesis structure.

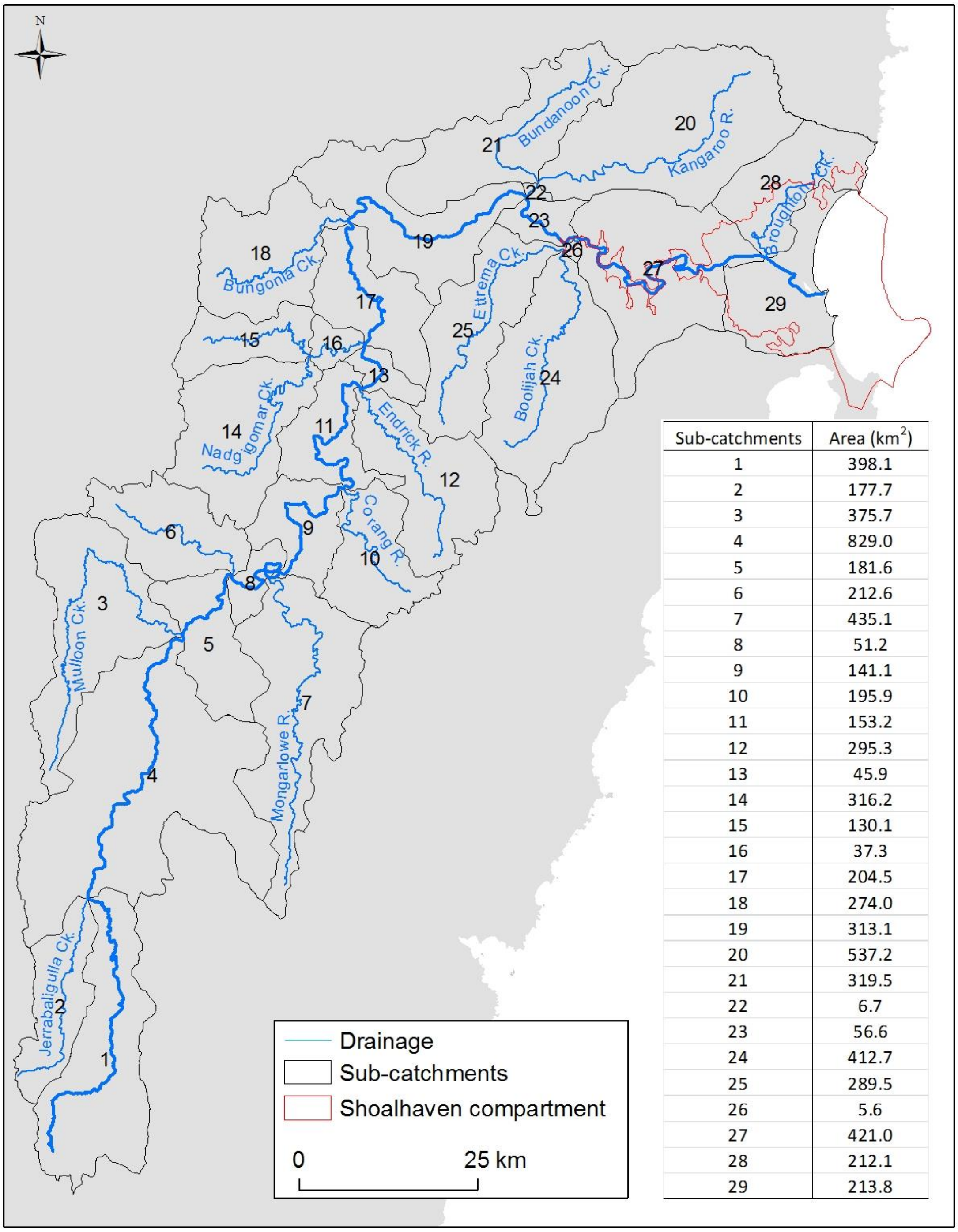
Table 2.1 Chapter 2 sub-sections in relation to sources and thesis structure.

Data and methods	Source	Chapter
Catchment morphometry and physical characteristics	Secondary	3
Catchment sediment yield	Primary	3
Bathymetry	Primary and secondary	3, 4, 5 and 6
Aerial photography	Secondary	4 and 6
Landsat imagery	Secondary	4 and 6
Airborne LiDAR	Secondary	4 and 5
Google Earth imagery	Secondary	4
Sidescan sonar	Primary	4 and 6
Bank erosion	Primary	4
Sediment Sampling	Primary	4, 5 and 6
Mineralogy	Primary	4, 5 and 6
Scanning Electron Microscope	Primary	4, 5 and 6
Beach monitoring at short time scale	Primary and secondary	5
Beach monitoring at decadal time scale	Primary	5 and 7
Shoalhaven Heads entrance monitoring	Secondary	5
Wave data	Secondary	5
Wave modelling	Primary	5

2.1 Catchment morphometry and physical characteristics

Morphometry of the Shoalhaven catchment was derived from the 1 second Shuttle Radar Topography Mission (SRTM) derived digital elevation model (Gallant et al., 2011) dataset. Therefore, elevation used to create the hypsometric curve and slope map had a 30 m pixel size. Rivers, streams and catchment subdivisions were derived from the SRTM dataset and inconsistencies were corrected by digitising with the aid of Landsat images, especially where flatter areas occurred. The Shoalhaven catchment subdivision resulted in a total of 29 sub-catchments based on the confluence of main tributaries (Figure 2.1). Sub-catchments varied from 5.6 km^2 (sub-catchment number

26), to 829 km^2 (sub-catchment 4). Stream length ranged from 2.6 km (sub-catchment 23) to 70.5 km (sub-catchment 3).



Sub-catchments	Area (km^2)
1	398.1
2	177.7
3	375.7
4	829.0
5	181.6
6	212.6
7	435.1
8	51.2
9	141.1
10	195.9
11	153.2
12	295.3
13	45.9
14	316.2
15	130.1
16	37.3
17	204.5
18	274.0
19	313.1
20	537.2
21	319.5
22	6.7
23	56.6
24	412.7
25	289.5
26	5.6
27	421.0
28	212.1
29	213.8

Figure 2.1 Drainage network of the Shoalhaven River with main river tributaries and catchment subdivisions.

Geology was digitised from the map in Nott (1990). Landuse was classified based on Landsat imagery and converted to 200 x 200 m grid format. Soil types and characteristics were derived from FAO-UNESCO (1978) in order to cover the whole

Shoalhaven catchment. This option was preferred to the use of the soil map at the published scale of 1:100,000 presented by Hazelton (1992) that only covered part of the Shoalhaven floodplain.

Annual rainfall over the catchment was calculated for specific years using the Bureau of Meteorology's monthly gridded dataset available at: http://www.bom.gov.au/jsp/awap/rain/index.jsp. Details about the high-quality set of historical climate analyses at spatial resolution of approximately 5 x 5 km can be found in Jones et al. (2009).

2.2 Catchment sediment yield

Sediment yield by the Shoalhaven catchment was calculated using the Langbein and Schumm (1958) method for specific rainfall values falling within individual sub-catchments. The method is based on figures of annual effective precipitation over the catchment not considering geologic or topographic factors (Figure 2.2). The sediment yield curve is fitted to data from the USA and relates high sediment yields to precipitation in the 150-650 mm range over desert/shrub and grassland areas due to the sparse vegetation cover, and moderate sediment yields to areas of higher rainfall but covered with forest.

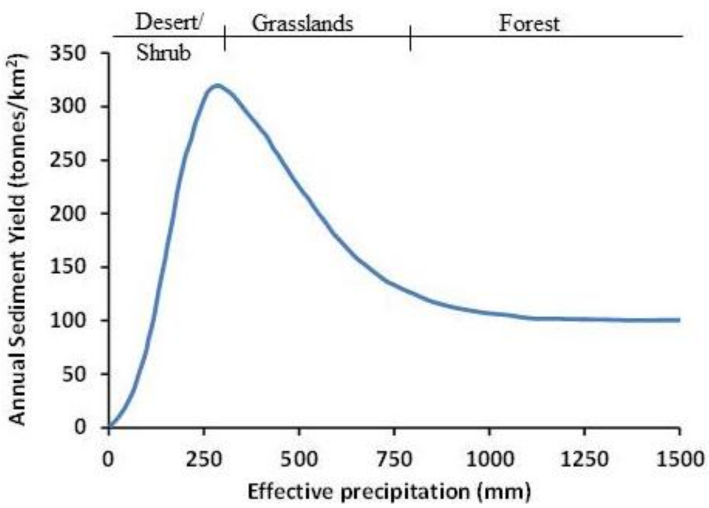


Figure 2.2 Annual sediment yield based on effective precipitation. Modified from Langbein and Schumm (1958).

The first step to estimate sediment yield for the Shoalhaven catchment consisted of calculating the spatial average rainfall for each of the sub-catchments over a calendar year. Then, individual rainfall values are used as effective precipitation values (abscissa) and fitted to the sediment yield curve to provide an annual sediment yield (ordinate) for the sub-catchment. The use of rainfall values instead of effective precipitation (precipitation adjusted for the effect of temperature) was adopted due to the complex and extended computations required for this task. Once the annual sediment yield is estimated for all the sub-catchments, values are summed to provide the annual sediment yield for the whole Shoalhaven catchment over a specific calendar year.

2.3 Bathymetry

Bathymetric survey of Lake Yarrunga, the reservoir formed after construction of Tallowa Dam in 1976, was carried out in May/2014 in order to calculate the volume of sediments trapped after dam construction. Approximately 54,000 points were collected using a CEEDUCER PRO – a dual channel echo sounder hydrographic survey system, with built-in DGPS and data logging. The survey covered an area of approximately 6 km^2, 83 % which had been surveyed previously in 2003 (Figure 2.3). Technical problems with the equipment hindered the density of data acquisition, whereas submerged hazards prevented acquistion of data in marginal areas such as Yarrunga Creek and parts of Bundanoon Creek.

Sediment deposition in Lake Yarrunga was calculated using the difference between the bathymetric survey conducted in 2014 and the April/2003 survey provided by Sydney Catchment Authority. Due to the technical problems that occurred during the 2014 campaign that resulted in sparse data with a lot of gaps, no DEM could be derived from the bathymetric soundings. However, an estimation of the sediment deposition in the 11 year interval was calculated using a total of 39 cross-sections: 12 on the Shoalhaven River side of the Lake, 21 on the Kangaroo River side, and 6 on Bundanoon Creek. Sediment deposition at individual cross-sections was calculated using the difference in cross-sectional areas between 2014 and 2003, and volumes were estimated using the average of consecutive cross-sectional areas multiplied by the distance between them. Volumes upstream from the uppermost cross-sections were simply calculated by multiplying the remaining lake distance by half of the cross-sectional area.

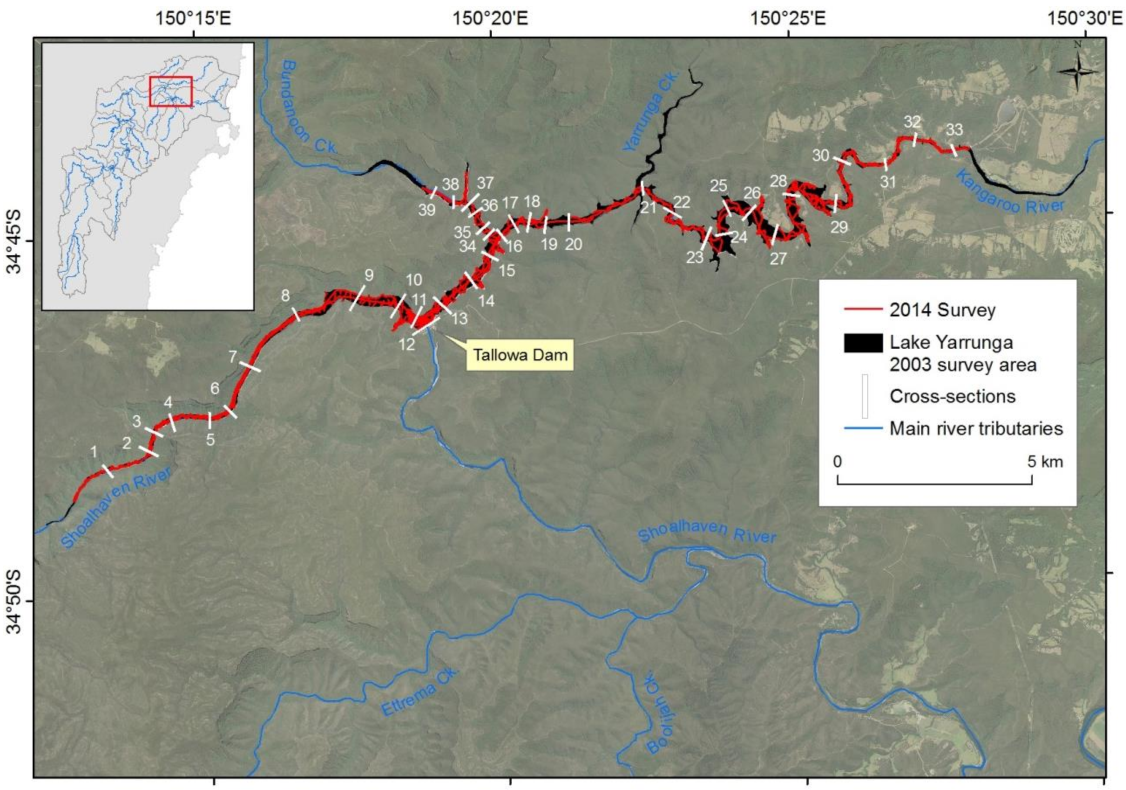


Figure 2.3 Lake Yarrunga bathymetric survey conducted in 2014. Background imagery © NSW Government. Land and Property Information (LPI) 2013.

Estuarine bathymetry was collected between Shoalhaven Heads and Crookhaven Heads in 2015, in order to compare to previous bathymetric surveys. Approximately 63,500 survey points were collected using the CEEDUCER PRO. Fieldwork was carried out between 18/12/2014 and 03/08/2015 and soundings were corrected using tide gauges located at Crookhaven Heads, Greenwell Point, Hay Street and Shoalhaven Heads (Figure 2.4). Previous bathymetric surveys covering Shoalhaven Heads and the entire Shoalhaven estuary in 1989 and 2006, respectively, as well as the entire Lake Wollumboola in 1991, were provided by OEH.

Approximately 10,500 survey points were digitised from the 1981 PWD's Shoalhaven River hydrographic survey plans that covered most of the estuary and the nearshore between Shoalhaven Heads and Crookhaven Heads. The plans were georeferenced, digitised and spatially adjusted using survey marks identified in the plans to account for the offset in the horizontal coordinates (Figures 2.4 and 2.5).

Specific offshore bathymetric surveys spanning parts of the study area during different years were provided by OEH and Geoscience Australia (Table 2.2).

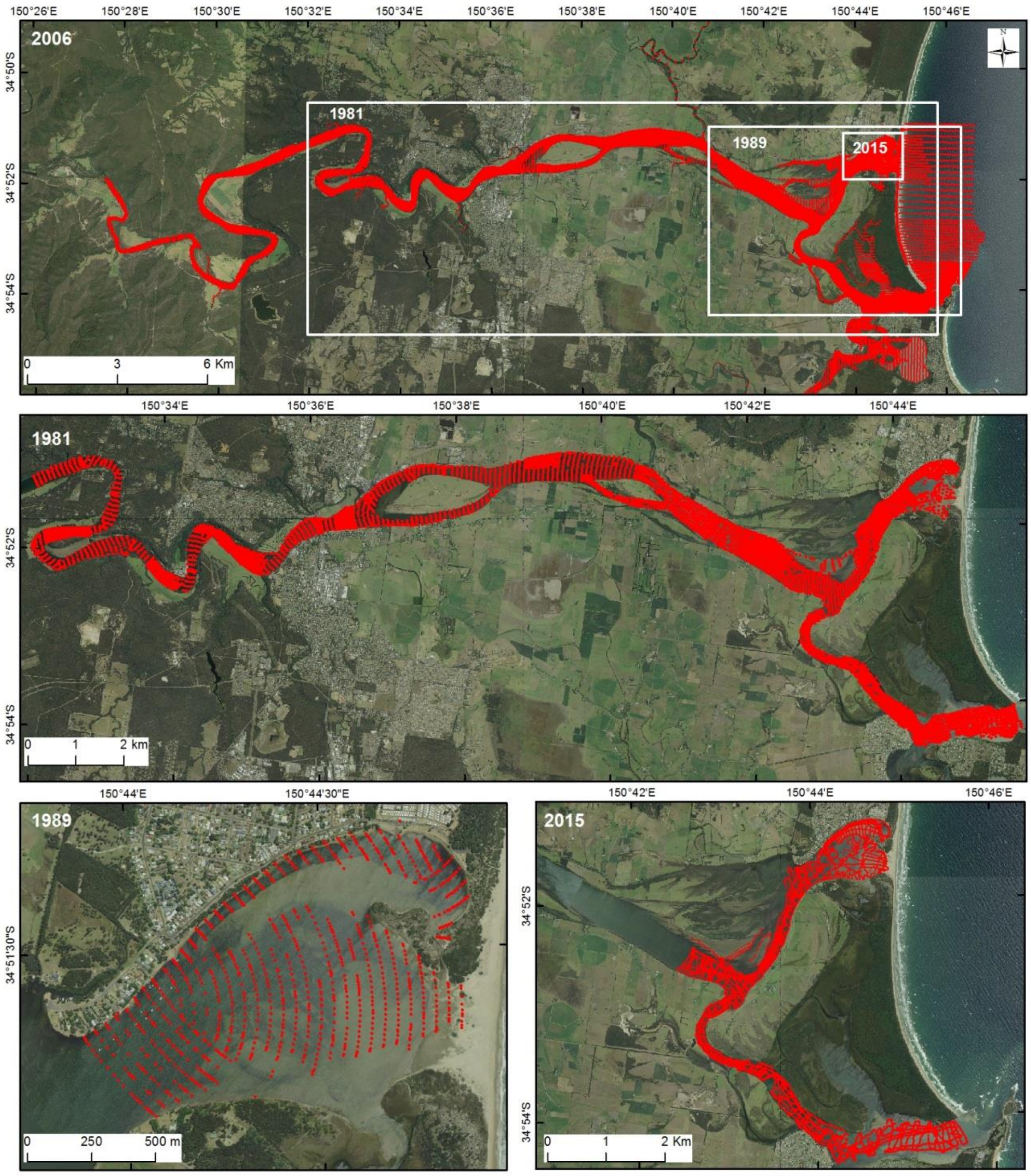


Figure 2.4 Estuarine bathymetric datasets showing previous surveys provided by OEH, covering the entire Shoalhaven estuary in 2006 and Shoalhaven Heads in 1989; Points digitised from the 1981 PWD's Shoalhaven River hydrographic survey plans; and bathymetry collected between Shoalhaven Heads and Crookhaven Heads in 2015. Background imagery © NSW Government. Land and Property Information (LPI) 2013; © NSW Government. Office of Environment and Heritage (OEH) 2006.

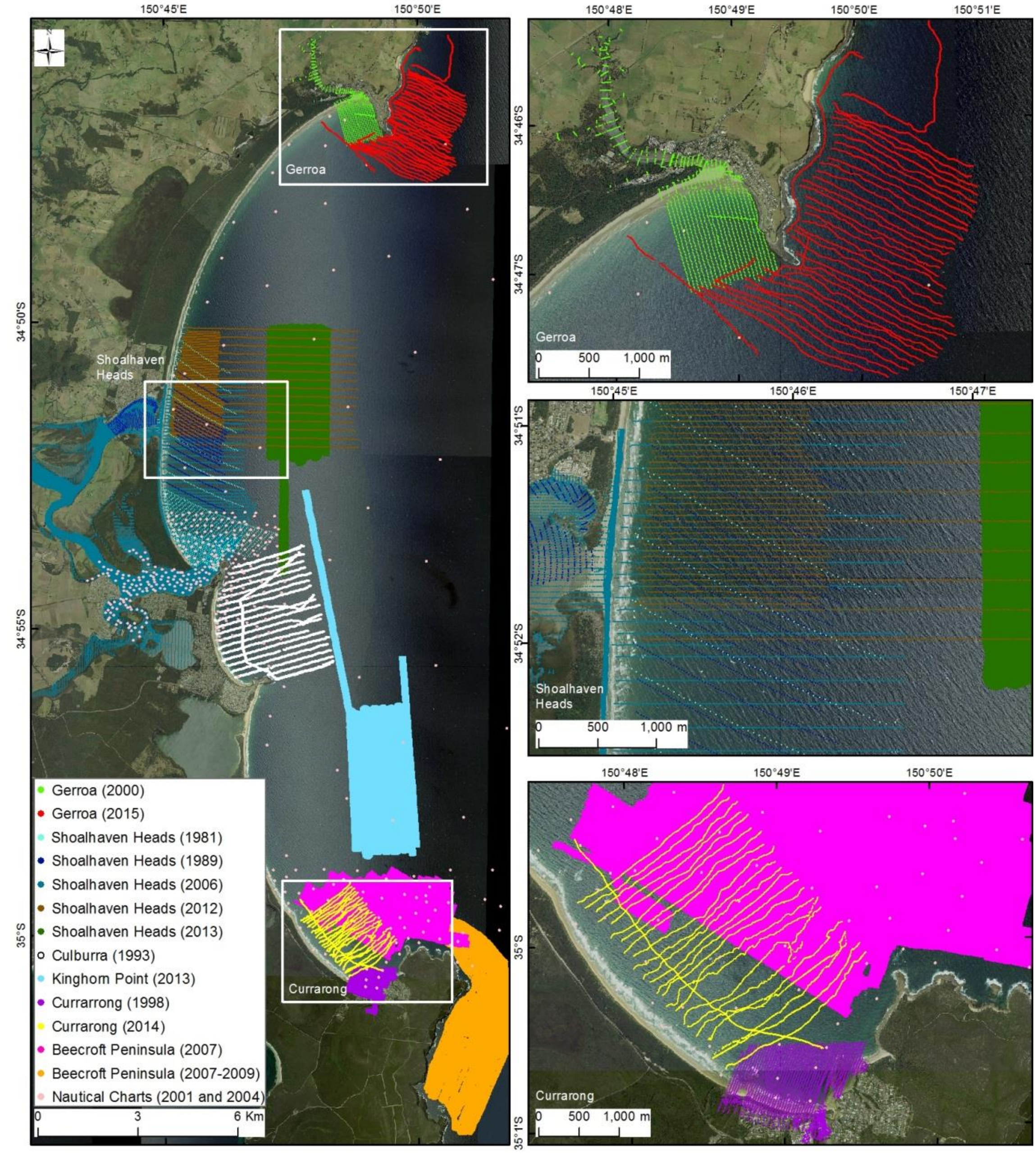


Figure 2.5 Offshore bathymetric datasets showing previous surveys provided by OEH; Points digitised from the 1981 PWD's hydrographic survey plans; and bathymetry collected at Currarong in 2014 (yellow lines), and Gerroa in 2015 (red lines). Background imagery © NSW Government. Land and Property Information (LPI) 2013; © NSW Government. Office of Environment and Heritage (OEH) 2014.

Digitisation of the nautical charts Aus00808 (2001), Aus00191 (2004) and Aus00193 (2004) filled in some of the gaps, whereas fieldwork at Currarong and Gerroa on 20/12/2014 and 30-31/03/2015, respectively (Figure 2.5), using a Humminbird 698SI echosounder, was carried out to provide details for both the southern and the northern end of the compartment. This study also used Geoscience Australia's 250 m grid to provide a general bathymetric layer for the NSW coast. The bathymetric data was used in the generation of DEMs, hypsometric calculation, and estimation of volume change over time. Geoscience Australia's 250 m grid was also used as an input to the wave model.

Table 2.2 Previous offshore bathymetric survey data used in the generation of DEMs and estimates of volume change

Area	Survey dates	Equipment	Organization
Gerroa	2000	Single Beam	OEH
Shoalhaven Heads	1981 1989 2006 2012 2013	Single Beam Single Beam Single Beam Single Beam Geoswath- Multi Beam	OEH OEH OEH OEH OEH
Culburra	1993	Single Beam	OEH
Kinghorn Point	2013	Geoswath- Multi Beam	OEH
Currarong	1998	Single Beam	OEH
Beecroft Peninsula	2007 2007-2009	Geoswath- Multi Beam Multi Beam	OEH Geoscience Australia

2.4 Aerial photography

This study used aerial photography taken between 1948 and 2014, acquired by several organizations including the Australian Survey Office (ASO), Airborne Warning and Control System (AWACS), Land and Property Information Centre (LPI) formerly Land Information Centre (LIC) and Air Maps Australia, at different scales (Appendix 1). These images were scanned and rectified using a 1st order polynomial transformation. Aerial photographs were widely used to create a retrospective of breaching times at Shoalhaven Heads and also to assess shoreline displacement using the vegetation line as the indicator. For this later use, extreme care was employed to georeference the images, as it directly influences the digitisation of the shoreline and the final product.

2.5 Landsat imagery

Landsat imagery was used to provide an historical perspective of change and processes in the study area. A total of 124 images from Landsat satellites 1, 2, 5, 7 and

8 were used (Appendix 2).The first available image was acquired on 05/11/1972 and the last one on 29/12/2015. RGB composites were created for each passage, excluding Band 6. The spatial resolution improved from 60 m (Landsat 1 and 2) to 30 m (Landsat 5) and finally 15 m (Landsat7 and 8) after merging the medium-resolution multispectral bands with the high-resolution panchromatic band (Pan-sharpening).

2.6 Airborne LiDAR

Light Detection And Ranging (LiDAR) is a technology that determines the distance to a surface using laser pulses. Distance is computed by measuring the time delay between transmission and detection of the reflected signal. Airborne LiDAR data covering the terrestrial environment was provided by the Shoalhaven City Council and the NSW Land and Property Information (LPI). The Shoalhaven Council contracted AAM Hatch Co. to collect the data from a fixed wing aircraft on 17/05/2001 and 21/08/2004, whereas the LPI started a standard LiDAR survey on 17/12/2010 and finished on 13/04/2011 (Figure 2.6).

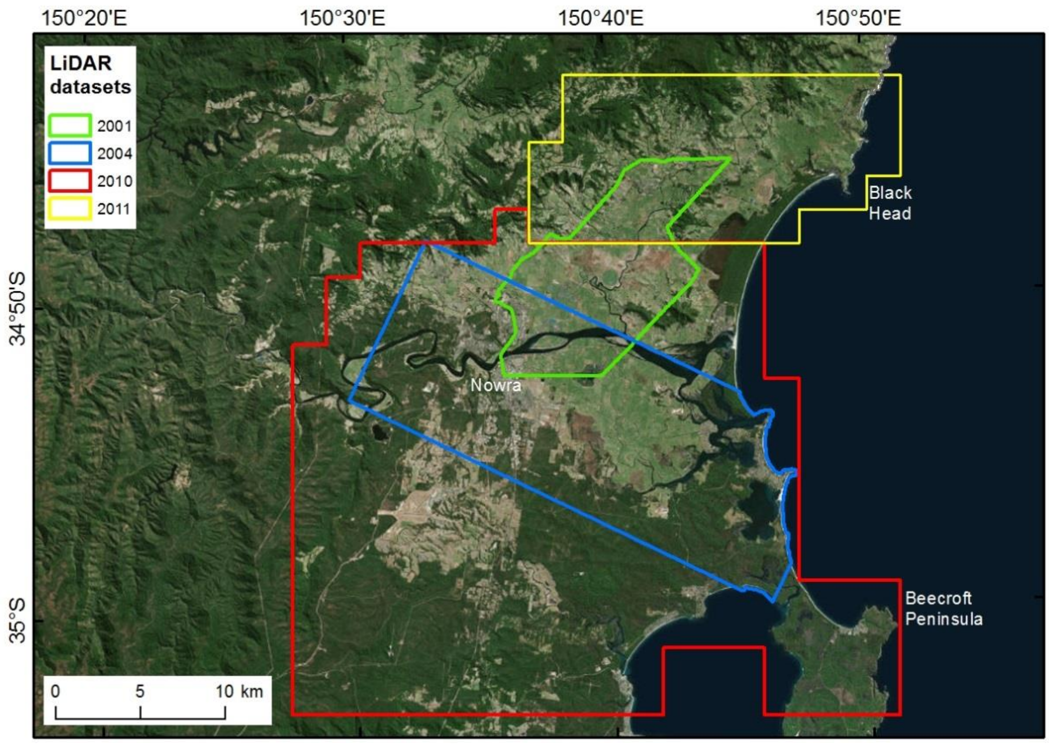


Figure 2.6 LiDAR datasets. Background imagery © LP DAAC.

LiDAR data was provided in 2 x 2 km tiles and data processing for this thesis consisted of converting LAS files into multi points, then to single points and finally creating TINs. The data was processed for bare ground using returned values with a minimum point density of 1 point/m^2. LiDAR data was used throughout this thesis in the generation of DEMs and follow up analyses involving volume calculations, hypsometric curves, topographic profiles and changes over time.

2.7 Google Earth imagery

This study also benefited from the use of high resolution images available on Google Earth. Images from 13/09/2005 to 17/01/2016 were used in the flood-tidal delta analysis in the Crookhaven channel.

2.8 Sidescan sonar

Concurrent to the offshore bathymetry aquisition at Currarong and Gerroa, the Humminbird 698SI also acquired high-resolution (455 kHz) sidescan sonar imagery to distinguish between rocky and sandy bottom. The equipment was also deployed to characterise different bedforms in the Shoalhaven estuary covering a total distance of 45 km (Figure 2.4) on 17-18/12/2014. As there is not consensus on appropriate nomenclature, the physical scale of bedform types was separated into two groups based on length (the horizontal distance between two consecutive crests) as adopted by Allen (1968): small-scale ripples were considered structures whose length was less than 60 cm whereas largescale ripples exceed this length. Bedform data was processed using SonarTRX software for the generation of georeferenced sonographs and imported into a GIS system for the digitisation of bedforms and identification of processes.

2.9 Bank erosion

Estuarine bank erosion assessment was conducted throughout the 50 km extent of the estuary (Figure 2.7) by completing field observation datasheets along both margins of the estuary in September/2015. The estuary was segmented into approximately 500 m reaches and information regarding the existence and extent of erosion, mechanism, bank armouring and type, as well as a photographic survey, was recorded for each of the 193 reaches.

Figure 2.7 Estuarine sidescan track, estuarine banks assessed for erosion, beach profile (SH1-SH4, CUL1-CUL3, WAR1-WAR3) locations and area of topographic survey using all-terrain vehicle (ATV). Background imagery © NSW Government. Land and Property Information (LPI) 2013.

2.10 Sediment Sampling

A comprehensive suite of estuarine, beach and offshore surficial sediments (n=209) was collected (Figure 2.8) to characterise these environments. Samples on the upper/middle estuary were collected in September 2013, whereas samples from the lower estuary were collected in December 2013. Beach samples (n=34) were collected in the swash zone in July 2014. Offshore samples (n=52) were collected at variable water depths (max 29 m) in May 2014 (Seven Mile Beach and Comerong Island), July 2014 (Culburra and Warrain-Currarong) and in March 2015 (Gerringong). Estuarine and offshore samples were collected using a square pipe dredge whereas a hand scoop was used to collect the beach samples.

In the laboratory, samples were washed for salt extraction, subsampled and dried. H_2O_2 (30 %) was used in some of the offshore samples before salt extraction, as the living molluscs within the samples decomposed and altered the colour of the sample.

To determine size fractions. approximately 150 g of sample was dry sieved at 0.5 phi intervals. Size fractions finer than 0 phi were determined by laser scanning using a Malvern Mastersizer 2000. Grain size statistics have been calculated using Folk and Ward (1957) formulae. Individual sample results were obtained by running the grain size distribution and statistic software Gradistat (Blott and Pye, 2001). Sample results were appended to georeferenced points, and maps of estuarine, and nearshore/offshore surficial sediments were created by Inverse Distance Weighted (IDW) interpolation. Sample coordinates and results of grain size analyses can be found in Appendix 3.

Figure 2.8 Estuarine, beach and offshore sediment sample locations. Samples selected for XRD are labelled. Background imagery © NSW Government. Land and Property Information (LPI) 2013.

2.11 Mineralogy

27 selected samples (Figure 2.8) were examined for mineralogical composition using X-ray diffraction (XRD). Size fractions finer than 0 phi were ground using Tema mill for 60 seconds, with care taken to avoid cross-contamination between samples. Following XRD analysis, results were corrected to the appropriate 2 theta spacing using Traces software, and quantification of mineral phases was performed by expressing the composition of crystalline material within each sample as percentage of dry weight using Siroquant software. For each sample, background values were subtracted and analysis conducted until minimum chi-square values were obtained.

2.12 Scanning Electron Microscope

Quartz grains from 19 samples were analysed using the JEOL scanning electron microscope (SEM) JCM6000. 16 medium sand (1-2 phi) grains from each estuarine (E58, E76, E93, E106, E113 and E122), beach (B2, B7, B11, B14, B18, B22, B27 and B33) and offshore (O10, O17, O29, O37 and O41) sample were selected at random using an optical microscope. Grains were placed in rows upon a metal specimen plug with double-sided sticky tape on it, and coated with gold for conductivity. Samples were analysed using a high vacuum mode with electrons accelerated to 10 kv after leaving the filament to generate Secondary Electron Images (SEI). SEM images were used to indicate a qualitative degree of roundness, sphericity and chemical weathering.

2.13 Beach monitoring at short time scale

Ten beach profiles were surveyed between 2013 and 2015 at the three embayments as part of this project (Figure 2.7). This was supplemented by previous beach surveys undertaken by the Water Research Laboratory (WRL) at University of New South Wales, between 2011 and 2012.

The surveys undertaken by WRL between February 2011 and December 2012, consisted of four beach profiles (SH1-SH4), as well as topographic surveys, using RTK-GPS at Seven Mile Beach-Comerong Island. The profiles were surveyed at a 1 m interval and scheduled at low tide in order to extend as far into the surf zone as possible. A total of 21 surveys at an average survey interval of 32 days occurred. Three-dimensional topographic surveys, spanning a 94 x 10^3 m^2 subaerial section of the beach adjacent to the Surf Life Saving Club (SLSC) at Shoalhaven Heads, have been performed each month. The RTK-GPS was mounted to an all-terrain vehicle (ATV) (Harley et al., 2011) collecting over an average of 3,500 irregularly spaced points per survey. Points were subsequently interpolated using IDW, as part of this thesis, and monthly volume was calculated.

Technical problems prevented collection of data during specific months at some locations (Table 2.3) and no surveys were conducted during the months of April 2012 and August 2012. Some volume calculations were also not possible due to missing data on the upper part of the profiles.

Table 2.3 Beach profiles and three-dimensional topographic surveys provided by the Water Research Laboratory between 2011 and 2012

Survey dates	**Profiles Seven Mile Beach-Comerong Island**				**ATV**	**Survey dates**	**Profiles Seven Mile Beach-Comerong Island**				**ATV**
	SH 1	**SH 2**	**SH 3**	**SH 4**			**SH 1**	**SH 2**	**SH 3**	**SH 4**	
17/02/2011	x	x	x		x	**09/01/2012**	x	x	x	x	x
22/03/2011		x	x		x	**07/02/2012**	x	x	x	x	x
20/04/2011		x	x			**21/03/2012**	x	x	x	x	x
17/05/2011		x	x	x	x	**07/05/2012**	x	x	x	x	x
17/06/2011	x	x	x	x	x	**07/06/2012**		x	x	x	x
14/07/2011	x	x	x	x	x	**31/07/2012**	x	x	x	x	x
17/08/2011	x	x	x	x	x	**20/09/2012**	x	x	x	x	x
16/09/2011	x	x	x	x	x	**15/10/2012**	x	x	x	x	x
25/10/2011	x	x	x	x	x	**12/11/2012**	x	x	x	x	x
29/11/2011	x	x	x	x	x	**10/12/2012**	x	x	x	x	x
16/12/2011	x	x	x	x	x						

Monthly beach profile surveys were undertaken specifically for this study at 10 sites (SH1-SH4, CUL1-CUL3, WAR1-WAR3) between December 2013 and November 2015 using RTK-GPS. At Seven Mile Beach-Comerong Island, it was opted to extend the surveys from the same four locations undertaken by WRL in 2011-2012 to increase the time series, whereas new bench marks were installed in the north, middle and south of Culburra and Warrain-Currarong beaches (Table 2.4). The profiles were surveyed at a 1 m interval across the beaches and scheduled at low tide. A total of

20 surveys at an average interval of 36 days were undertaken. Technical problems prevented the collection of data during specific months at some locations and no surveys were conducted during the months of June 2014, January 2015, April 2015 and May 2015.

Table 2.4 Beach profile surveys undertaken for this study at Seven Mile Beach-Comerong Island, Culburra and Warrain-Currarong beaches between 2013 and 2015.

Survey dates	**Profiles Seven Mile Beach-Comerong Island**				**Profiles Culburra**			**Profiles Warrain-Currarong**		
	SH 1	**SH 2**	**SH 3**	**SH 4**	**CUL 1**	**CUL 2**	**CUL 3**	**WAR 1**	**WAR 2**	**WAR 3**
7-8/12/2013			x		x	x	x	x	x	x
3-4/01/2014	x	x	x	x	x	x	x	x	x	x
1-2/02/2014	x	x	x	x	x	x	x	x	x	x
1-2/03/2014	x	x	x	x	x	x	x	x	x	x
29-31/03/2014	x	x	x		x	x	x	x	x	x
25-26/05/2014	x	x	x	x	x	x	x	x	x	x
12-14/07/2014	x	x	x	x	x	x	x	x	x	x
13-14/08/2014	x	x	x	x	x	x	x	x	x	x
9-10/09/2014	x	x	x	x	x	x	x	x	x	x
8-9/10/2014	x	x	x	x	x	x	x	x	x	x
7,19/11/2014	x	x	x	x	x	x	x	x	x	x
6-7/12/2014	x	x	x	x	x	x				
4-5/02/2015	x	x	x	x	x	x	x	x	x	x
20-21/03/2015	x	x	x	x	x	x	x	x	x	x
11-12/06/2015	x	x	x	x	x	x	x	x	x	x
9-10/07/2015	x	x	x	x	x	x	x	x	x	x
2-3/08/2015	x	x	x	x	x	x	x	x	x	x
25/09/2015	x	x	x							
29-30/10/2015	x	x	x		x	x	x	x	x	x
26-29/11/2015	x	x	x	x	x	x	x	x	x	x

2.14 Beach monitoring at decadal time scale

Georeferenced aerial photographs (Appendix 1) were used to monitor the shoreline change over the past 65 years. For this, five 50 m-spaced beach normal transects were taken at each of the ten sites used during the beach monitoring between 2013 and 2015 (Figure 2.7). Then, the first line of dense vegetation on the dune was digitised and distance from the more recent image calculated for each of the five transects at each of the 10 sites. Values per site were averaged out and plotted in a spread sheet.

2.15 Shoalhaven Heads entrance monitoring

Elevation points were collected using a RTK-GPS at the beach-berm that separates the estuary from the nearshore at Shoalhaven Heads by Shoalhaven City Council and survey data was provided for dates presented in Table 2.5. Surveyed dates with restricted or poor coverage of the area were discarded. Elevation points were interpolated using IDW to create monthly DEMs of the beach-berm. Monthly volumes were calculated and plotted in a spreadsheet.

Table 2.5 Dates of Shoalhaven Heads surveys provided by Shoalhaven City Council

Survey dates		
05/06/2013	28/01/2014	10/12/2014
03/07/2013	03/04/2014	10/08/2015
09/10/2013	11/06/2014	08/09/2015
13/11/2013	11/08/2014	15/10/2015
12/12/2013	02/10/2014	

2.16 Wave data

Wave data for the wave buoys located offshore of Batemans Bay and Sydney, 130 km south and 150 km north, respectively, of Shoalhaven Heads was provided by Manly Hydraulics Laboratory. Data covering the period between 2010 and 2016 was used to characterise past storms and as input to generate wave refraction diagrams.

2.17 Wave modelling

A finite-difference Steady-State Spectral Model (STWAVE), formulated on a Cartesian grid (0.5 km) and based on the wave action balance equation that simulates depth-induced wave refraction and shoaling (Smith et al., 2001) was used to estimate nearshore wave propagation. The model describes quantitatively the change in wave parameters between the offshore and nearshore, producing wave refraction diagrams for different wave conditions. Geoscience Australia's 250 m bathymetric grid, wave data from Manly Hydraulics Laboratory, wind data and tidal amplitude were used as input for the model.

Chapter 3: Catchment Yield

This chapter presents an estimation of the annual average fluvial sediment yield to the Shoalhaven coastal compartment. After a short introduction to the fluvial systems that discharge into the study area, subsequent sections provide information about the Shoalhaven catchment morphometry, physical characteristics and rainfall patterns. Later on, sediment yield using the Langbein and Shumm (1958) method, sediment deposition at Lake Yarrunga and sediment yield downstream of Tallowa Dam are estimated for the Shoalhaven catchment. These sections were designed not only to characterise the physical aspects of the catchment but mostly to calculate the fluvial sediment delivery to the Shoalhaven estuary. The sediment volume difference between the fluvial yield and the amount that is trapped within the estuary is going to be used to balance the budget of the tertiary level Seven Mile Beach-Comerong Island compartment in Chapter 7. Finally, a summary of the findings in terms of sediment yield is presented in the last section.

3.1 Introduction

Four fluvial systems discharge into the Shoalhaven coastal compartment. The Shoalhaven River and the Crooked River discharge into the Seven Mile Beach-Comerong Island tertiary level compartment, whereas the Coonemia and Currarong creeks discharge into the Warrain-Currarong tertiary level compartment. No major system discharges into Culburra (Figure 1.1).

The Shoalhaven is the 6th biggest catchment (7,151 km^2) of NSW, that debouches into the Tasman Sea and by far the most important fluvial system of the Shoalhaven coastal compartment. The main stream of the catchment is 340 km long and follows a S-N direction for about the first 2/3 of its length and then turns east before reaching the Pacific Ocean.

The catchment is composed of two major geologic provinces. The upper and middle catchment lie across the Palaeozoic Lachlan Fold Belt, whereas the lower section is incised through the southern Sydney Basin (Nott, 1990).

A temperate, subhumid climate (Köppen type Cfb) is experienced in most of the upper and middle catchment, with average annual rainfall of 900 mm for the whole catchment. The rainfall pattern is spatially variable with approximately twice the amount of rainfall in the lower catchment than further upstream (Carvalho and Woodroffe, 2015). Average mean daily temperatures reach 21°C in January and 11°C in July on the coastal plain (Umitsu et al., 2001).

The long-term drainage evolution in the Shoalhaven catchment was studied by Nott (1992). He provided a record of stream behaviour and showed that the Shoalhaven River and many of its tributaries have maintained almost the same course since at least the very early Tertiary.

Changes in streamflow in the upper Shoalhaven Valley in response to modifications of catchment vegetation were studied by Aston and Dunin (1980) by simulating the consequences of land-use change. They suggested that pasture improvements in the subcatchments would lead to a significant reduction of up to 28 % in streamflow.

Another major alteration in the catchment happened during the construction of Tallowa Dam in the mid 1970's, forming Lake Yarrunga. Tallowa Dam, a engineering structure whose sediment trap efficiency was calculated as 88 % (Boyd et al., 1977), has a catchment of approximately 5630 km^2 (77.7 %) and was created to divert part of the river's water to the Hawkesbury basin in order to augment the water supply of Sydney. Downstream from Tallowa Dam, only two major tributaries exist. The first is located 12 km downstream from the dam, on the right bank, and is formed by the confluence of Boolija and Ettrema creeks, whereas the other, Broughton Creek, is a tributary that discharges into the estuary, 7 km downstream from Nowra Bridge.

Between 1900 and 2004, the average annual flow of the Shoalhaven River at Tallowa Dam was 1,034.9 GL (Boyes, 2006), and a recent provision of almost 30 % of the annual water requirements of Australia's largest city, resulted in extended periods of relatively invariant and low volume flow releases downstream of the dam (Reinfelds et al., 2010).

The Crooked River is an 8 km-long partly perennial stream (GNR, 2017) that flows from the mountains (approximately 300 m of altitude) on the west of Gerringong and discharges at Gerroa. For most of its small catchment (area of approximately 30 km^2) original vegetation has been cleared and replaced with pasture. The Crooked River forms a small barrier estuary in its lower reach.

Coonemia Creek catchment is approximately the same size as the catchment of Crooked River (Roper et al., 2010). However, over most of its catchment original vegetation is preserved. The creek rises at only 70 m of altitude and forms a saline coastal lagoon, near Warrain, in the last 2 km of its 8 km length, named Lake Wollumboola.

Currarong Creek, located on the southern part of Warrain-Currarong tertiary level compartment, drains a much smaller catchment of approximately 12 km^2 (Roper et al., 2010) from its headwaters (80 m of altitude) at Beecroft Peninsula to a very small estuary in the village of Currarong. The catchment vegetation is sparse and mostly composed of small trees and shrubs.

3.2 Shoalhaven catchment morphometry and physical characteristics

Figure 3.1 depicts the Shoalhaven catchment topography and hypsometric curve. The Shoalhaven catchment is bordered mainly by the Hawkesbury River to the north/northeast, the Murrumbidgee River to the southwest and the Moruya River to the east. The maximum elevation in the catchment is 1440 m and the hysometric curve shows that the Shoalhaven is far from an equilibrium state as defined by Strahler (1952). The existence of broad drainage divides in the middle catchment mean that remains of the original surface still exists there. However, a large proportion of the upland surface has been geologically transformed into valley-wall slopes and only 11 % of the total area is located above 720 m of altitude (0.5 of the relative height).

The catchment geology, as well as slope, landuse and soil types is depicted in Figure 3.2. The headwaters are located approximately 40 km from the sea, in the hilly to mountainous highlands (1400 m of elevation) of the geologically complex Palaeozoic Lachlan Fold Belt, composed of steeply dipping Ordovician metasediments, Siluro-Devonian volcanic rocks and Devonian granites (Nott, 1992). Bedload originating from the steep but narrow valleys, is mostly composed of medium to coarse grained sands, from the granite batholiths, and gravels of dacite, chert and quartzite (Nott et al., 2002).

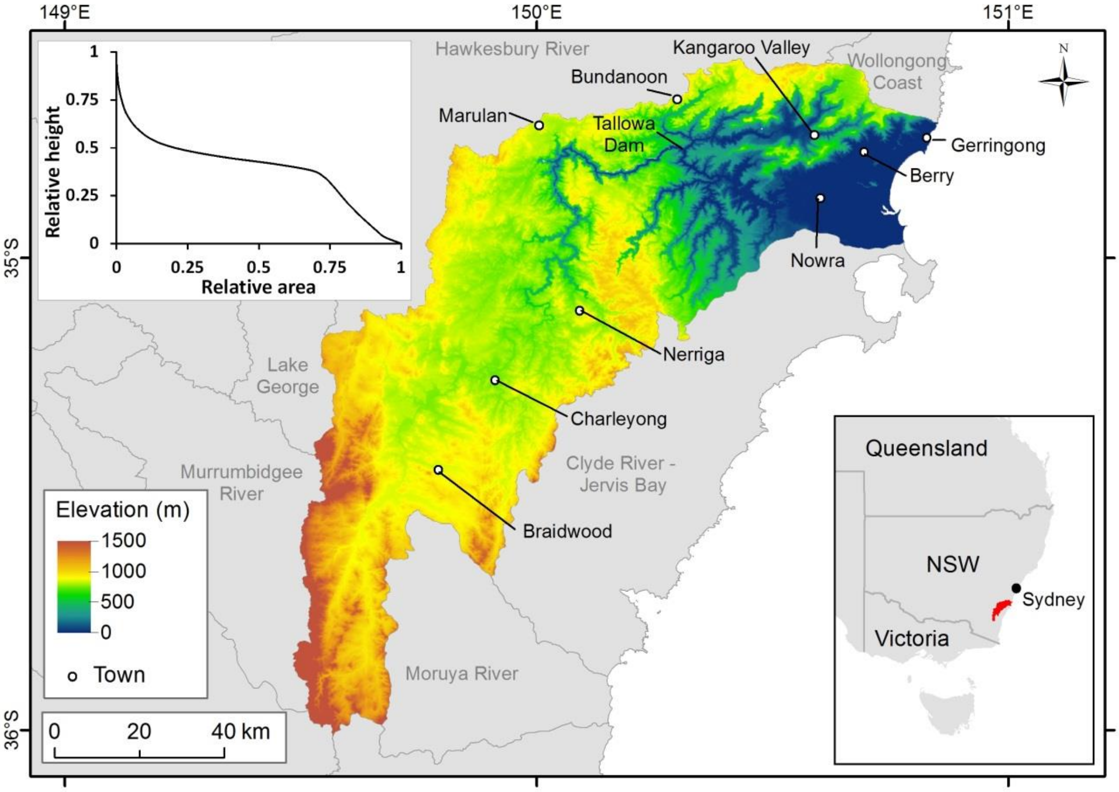


Figure 3.1 Topographic map, hypsometric curve (Dimensionless x and y axis) of the Shoalhaven catchment and location of adjacent catchments. Topographic data © Commonwealth of Australia (Geoscience Australia) 2009.

The middle catchment crosses the same geological province, and therefore, the same bedload type is found, as in the upper catchment. However, the topography falls to 600-700 m in height and is dominated by an undulating surface of low relief due partly to the extensive sheet of Tertiary sediments covering the plain (Nott, 1992). Further downstream, into the northern/northeastern parts of the Shoalhaven Plain, the river and its tributaries have carved steep-sided gorges of up to 500 m and widths of approximately 2.5 km, where the horizontally-bedded sandstones of the Sydney Basin overlie the steeply dipping Palaeozoic strata (Nott et al., 1996).

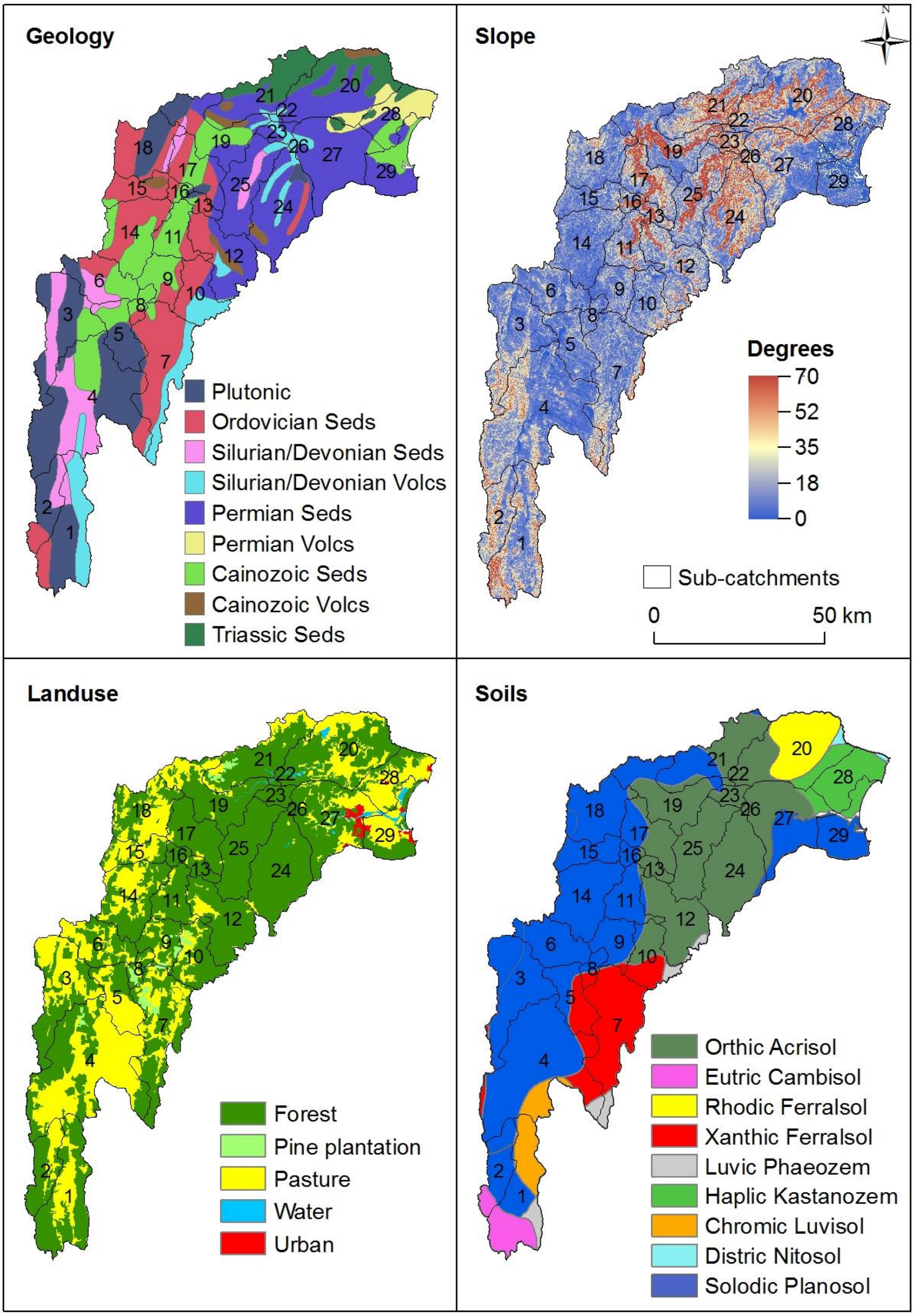


Figure 3.2 Geology, slope, landuse and soil types within the Shoalhaven catchment associated to subdivisions presented in Figure 2.1. Geology digitised from Nott (1990); Slope derived from SRTM data; Landuse classified based on Landsat imagery and; Soil types derived from FAO-UNESCO (1978).

The lower Shoalhaven is composed of the near horizontally-bedded Permo-Triassic sandstones and siltstones (Nott, 1992), that are found to occur on two Shoalhaven Group units, namely Megalong Conglomerate and the Berry Formation on the western margin of the Sydney Basin (Harwood, 1999). The Megalong Conglomerate is a sandstone and conglomerate facies unit that consists of a poorly sorted polymict conglomerate with quartzite and diorite clasts towards the base that grades to medium-grained lithic sandstone towards the top (Hutton and Feldtmann, 1996). The Berry Formation is a massive micaceous feldspathic siltstone to fine-grained litharenite (Bowman, 1974) that weathers rapidly (Harwood, 1999).

At Nowra, the river leaves its narrow sandstone gorge and flows across gently undulating Holocene deltaic-estuarine plains, that extend for approximately 13 km to the Tasman Sea. The plains overlie Pleistocene alluvium, which is exposed at or near the surface in several locations (Young et al., 1996, Umitsu et al., 2001).

Slopes in the Shoalhaven catchment have an average of 7.7°, but reach a maximum of 70° in sub-catchment 19, whereas slopes greater than 50° were encountered in sub-catchments 11-13, 16-21, 23-25, 27 and 28. A clear distinct flatter area dominates most of the sub-catchments 3-10, 14, 15 and 29.

Five classes of landuse based on Landsat image classification were observed in the catchment. Forest and pasture lands dominate almost 98 % of the catchment area. Forested areas cover 4,728 km^2 (65.3 %) and are found in every single sub-catchment, but are concentrated in a polygonal area centered at sub-catchment 25 and on the high elevation parts of the upper Shoalhaven catchment. Pasture areas cover 2,351 km^2 (32.5 %) and occupy most of the remaining area of the catchment, especially where flatter slopes occur, both around the 600 m of altitude and the floodplain areas. Pine forest plantations are restricted to 78 km^2 (1.1 %) and are found only in sub-catchments 4, 7-10 and 21, whereas, urban areas in the lower catchment covering the towns of Nowra, Berry and Culburra, occupy 43 km^2 (0.6 %). Water courses and reservoirs cover the remaining 40 km^2 (0.5 %) of the catchment.

Nine different classes of soil types are found in the catchment. Solodic Planosols are spread over 3243 km^2 (44.9 %) occupying the western part of the catchment and also the south side of the floodplains. This soil type is usually 0.6 to 1 m thick with A horizons ranging from brownish grey to brown and reddish brown sands, sandy loams and loams. Orthic Acrisols cover 2072 km^2 (28.7 %) of mostly forested areas, have texture profiles that become increasingly clayey with depth, and coarse to medium-textured A horizons ranging from brownish/dark grey to yellow-grey and grey-brown. Ferralsols are found in both Rhodic (304 km^2 – 4.2 %) and Xanthic (712 km^2- 9.9 %) varieties. Ferralsols are clayey throughout or become increasingly clayey with profiles ranging from 1 to 2 m depth. A horizons are very dark brown to dark reddish brown (Rhodic) and grey or grey-brown (Xanthic) sandy loams, loams, clay loams or light clays. Haplic Kastanozems are usually 0.6 to 1.5 m deep, occupying 394 km^2 (5 %) mostly in the northern part of the floodplains, and having uniform medium textured profiles with A horizons distinctly organic silty or fine sandy loams or clay loams of 10 to 20 cm thick. Most of the Chomic Luvisols are hardsetting with 0.5 to 1 m thick soil depths that have distinct texture contrast profiles with coarse or medium surface soils overlying clay subsoils, occupying 217 km^2 (3 %). Eutric Cambisols (168 km^2- 2.3 %) have uniform medium-textured profiles ranging in depths from 0.6 to 1 m and overlying C horizons of weathered rock. Luvic Phaeozems are very friable soils when moist. Their texture profiles become increasingly clayey with depth and occupy an area of 121 km^2 (1.7 %). Dystric Nitosols are deep soils with thick argillic B horizons, with texture profiles that become clayey with depth, occupying only 20 km^2 (0.3 %).

3.3 Rainfall

The spatial distribution of rainfall for the Shoalhaven catchment for the calendar years of 2011-2014 using the Bureau of Meteorology's monthly gridded dataset is depicted in Figure 3.3. The spatial average of annual rainfall for the catchment was 900 mm (2011), 970 mm (2012), 955 mm (2013) and 924 mm (2014), with rainfall distribution in different parts of the catchment ranging from 558 to 1891 mm in 2011, 745 to 1460 mm in 2012, 609 to 1905 mm in 2013, and 559 to 1615 mm in 2014.

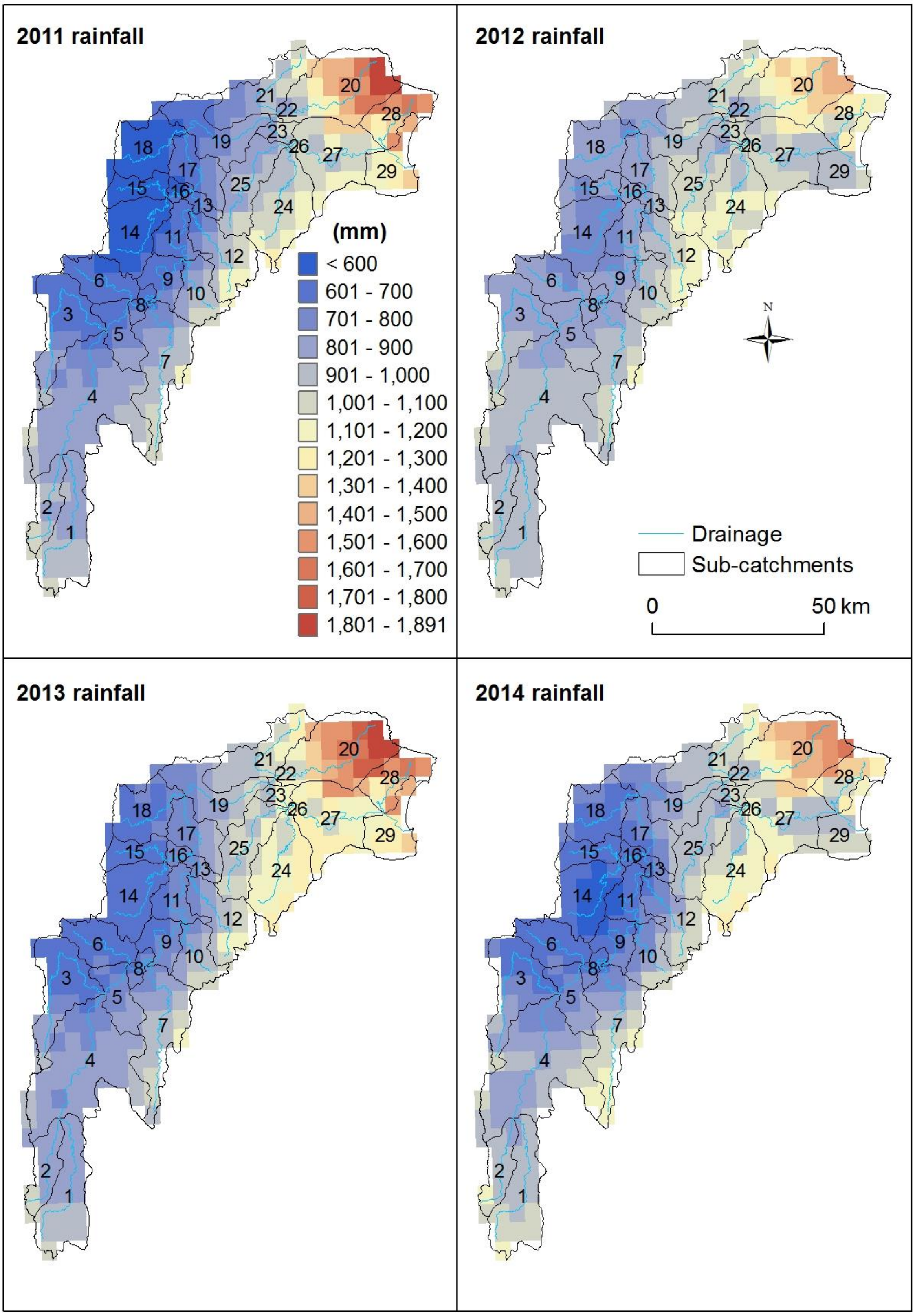


Figure 3.3 Spatial distribution of annual rainfall for the calendar years of 2011-2014 using the Bureau of Meteorology's monthly gridded dataset, showing considerably more precipitation on the coast than in other parts of the catchment. Drainage network with main river tributaries and catchment subdivisions are represented in the maps.

The four analysed years had a similar spatial pattern of higher precipitation in the eastern part (sub-catchments 20-29) of the catchment and lower in the western part (sub-catchments 3, 6, 14, 15 and 18). The annual rainfall of 900 mm registered in 2011 is considered the average figure for the Shoalhaven catchment according to Carvalho and Woodroffe (2015) (Appendix 4), who showed that much higher annual values (up to 1970 mm) happened during the decades of 1950 and 1970, whereas drier than normal years (approximately 500 mm) occurred in the beginning of 1940’s, 1980’s and the second half of 1960’s.

3.4 Sediment yield using the Langbein and Schumm (1958) method

Between 2011 and 2014, the annual sediment yield from the Shoalhaven catchment estimated using the Langbein and Schumm (1958) method ranged from 798,956 to 914,186 tonnes. These figures consist of sediment produced by the 22 sub-catchments upstream (1-22) from Tallowa Dam plus the seven sub-catchments downstream (23-29) from the dam (Table 3.1).

The annual sediment yields downstream from Tallowa Dam ranged from 165,604 to 169,031 tonnes per year, whereas the upstream yields varied from 629,924 to 745,320 tonnes per year. Assuming that the 88 % trap efficiency reported by Boyd et al. (1977) for the reservoir is correct, annual sediment yields delivered from the upstream sub-catchments escaping Tallowa Dam (12 %) would be 75,591- 89,438 tonnes (Table 3.2).

The total sediment yields delivered to the estuary corresponds to the 12 % that escapes Tallowa Dam plus the sediment yields produced by the downstream catchments. Summing up these two values, the estimated annual sediment yields ranged from 244,622 to 258,324 tonnes. Assuming that 1 tonne of sediment is the equivalent of 0.65 m^3 (sediment density ± 1550 kg/m^3), the annual sediment yield for the Shoalhaven catchment ranged from 159,004 to 167,911 m^3 between 2011 and 2014.

There are many uncertainties in the figures presented here, not only because there are considerable limitations to the method that does not differentiate between geology, soil, topography or landuse types, nor accounts for variation in temperature, rainfall intensity, seasonality or storm events. The annual figures presented by this method should be seen as overestimations of the actual yields because the Bureau of

Meteorology's monthly gridded precipitation values used here are derived from interpolation of rain gauges throughout the area (Jones et al., 2009), whereas Langbein and Schumm used figures of effective precipitation based on well-stablished relationships with runoff. In a climate with temperature greater than 10° C, the effective precipitation is less than the actual rainfall (Langbein and Schumm, 1958), therefore, for the Shoalhaven catchment, the yields presented above are overestimated.

Table 3.1 Estimated sediment yield between 2011 and 2014 calculated using the Langbein and Schumm (1958) method based on rainfall input for individual sub-catchments presented in Figure 2.1.

Sub-catchment	2011 Rainfall (mm)	2011 Yield (Tonnes)	2012 Rainfall (mm)	2012 Yield (Tonnes)	2013 Rainfall (mm)	2013 Yield (Tonnes)	2014 Rainfall (mm)	2014 Yield (Tonnes)
1	925	44,192	959	43,396	914	44,192	1,013	42,202
2	931	19,544	964	19,366	919	19,721	976	19,188
3	711	53,347	905	42,076	716	52,595	762	49,214
4	845	97,821	934	91,189	837	99,479	897	93,676
5	723	25,242	871	21,066	761	23,971	768	23,608
6	617	36,358	817	25,940	645	34,019	648	33,807
7	930	48,298	980	46,993	945	47,863	991	46,558
8	694	7,425	842	6,094	735	6,965	704	7,323
9	683	21,024	828	16,932	715	19,754	651	22,294
10	924	21,742	1,000	20,958	930	21,742	886	22,329
11	630	25,428	816	18,688	685	22,824	620	26,041
12	935	32,478	1,030	31,297	957	32,182	906	33,068
13	711	6,470	906	5,140	807	5,690	736	6,195
14	578	59,451	780	40,477	625	52,810	602	55,973
15	566	25,104	805	16,129	644	20,941	645	20,941
16	595	6,718	820	4,553	714	5,262	657	5,859
17	687	30,262	905	23,105	805	25,354	762	26,990
18	586	50,407	840	32,600	689	40,271	710	38,901
19	737	42,582	927	34,754	870	36,007	846	36,946
20	1,425	54,261	1,250	54,261	1,523	54,261	1,364	54,261
21	889	36,420	993	34,183	1,007	33,225	990	34,183
22	925	748	973	728	1,074	701	1,005	714
23	925	6,279	973	6,110	1,074	5,883	1,005	5,996
24	1,065	42,918	1,096	42,505	1,168	42,505	1,109	42,505
25	902	32,718	1,031	30,691	1,028	30,691	966	31,270
26	1,087	572	1,018	588	1,206	566	1,078	572
27	1,087	43,367	1,018	44,630	1,206	42,946	1,078	43,367
28	1,448	21,417	1,148	21,629	1,467	21,417	1,222	21,417
29	1,249	21,595	993	22,878	1,272	21,595	1,022	22,664
Total		**914,186**		**798,956**		**865,434**		**868,063**

Table 3.1 Estimated annual sediment yield summary using the Langbein and Schumm (1958) method between 2011 and 2014 for the Shoalhaven catchment, sub-catchments upstream, downstream and escaping (12 %) Tallowa Dam, as well as delivered to the estuary. Conversion from tonne to m^3 based on sediment density of ± 1550 kg/m^3 (1 tonne = 0.65 m^3)

	2011	**2012**	**2013**	**2014**
Catchment yield (tonnes)	914,186	798,956	865,434	868,063
Upstream sub-catchment yield (tonnes)	745,320	629,924	699,830	700,271
12 % Upstream yield (tonnes)	89,438	75,591	83,980	84,032
Downstream sub-catchment yield (tonnes)	168,886	169,031	165,604	167,791
Total yield to the estuary (tonnes)	258,324	244,622	249,584	251,823
Total yield to the estuary (m^3)	167,911	159,004	162,230	163,685

Despite the uncertainties related to sediment yields and bedload, a great variability in interannual yields can be assumed based on the variability of rainfall in the past 130 years and therefore in the water discharge to the estuary. Carvalho and Woodroffe (2015) analysed the catchment rainfall since 1885 and showed that average annual rainfall for the Shoalhaven catchment ranged from 1970 mm (1950) to 440 mm (1982).

3.5 Sediment deposition at Lake Yarrunga

Sediment deposition at Lake Yarrunga was calculated using the difference between the bathymetric surveys conducted in 2014 and 2003 using a total of 39 cross-sections (Table 3.3).

On the Shoalhaven River side of the reservoir - western side of the dam (Figure 3.4), the volume difference between the bathymetric surveys conducted between cross-sections 1 and 12 showed deposition of 1,338,830 m^3, over 11.2 km in length. Considering that the reservoir extends for another 2,250 m further upstream from cross-section 1, and multiplying by half the depositional area of cross-section 1 (38 m^2), then an extra 42,750 m^3 must be added to the 1,338,830 m^3, equating to approximately 1,380,000 m^3 of sediment trapped by Tallowa Dam in 11 years, or an average rate of approximately 125,000 m^3/y.

On the Kangaroo River side - eastern side of the dam (Figure 3.5), the volume difference between the bathymetric surveys using cross-sections 13 and 33, along approximately 21 km in length, equates to 3,152,389 m^3. Considering an extra of 490 m between cross-section 13 and the confluence of the Shoalhaven River side of the lake, multiplying by the cross-section 13 depositional area (190 m^2), and 4,500 m upstream from cross-section 33, multiplying by half the depositional area of cross-section 33 (72 m^2), then, an extra volume of 93,100 m^3 and 162,000 m^3, respectively must be added, equating to a volume of 3,407,489 m^3 for the Kangaroo River side of the lake. On top of that, the volume deposited by Bundanoon River and Yarrunga creeks must be added to provide a more complete figure.

The six cross-sections (34-39) on Bundanoon River, along 1,531 m in length, provided an estimated volume of 201,401 m^3 of sediment deposited. Considering an extra 2,400 m upstream from cross-section 39, multiplying by half of its depositional area (22 m^2), equals an extra 26,400 m^3 of sediment, that added to 201,401 m^3, equates to a volume of approximately 227,801 m^3. Regarding Yarrunga Creek, since no bathymetric data was collected in 2014, an estimation can only be made based on the lake length (approximately 4,500 m) and catchment size (approximately 40 km^2). Judging from these two parameters and comparing to values calculated for Bundanoon Creek catchment, a volume of 100,000 m^3 was assigned for it.

The total volume for the Kangaroo River side of the Lake Yarrunga is the sum of 3,407,489 m^3, 227,801 m^3 and 100,000 m^3. This equates to approximately 3,735,000 m^3 of sediment trapped in 11 years, or an average rate of 340,000 m^3/y, between 2003 and 2014.

Summing up both sides of the lake, a total volume of deposition of approximately 5,100,000 m^3 occurred in between 2003 and 2014, or an average annual deposition of approximately 465,000 m^3/y.

There are at least two major implications for these findings related to Shoalhaven catchment yields. The first one is related to the fact that approximately three times more sediment was deposited on the Kangaroo River side of Lake Yarrunga between 2003 and 2014, than on the Shoalhaven River side, implying that, despite the much smaller catchment size draining to the eastern side of the dam (857 km^2), when compared to the western side (4,767 km^2), the sediment yield there is much higher than the yield by the Shoalhaven River upstream from Tallowa Dam.

Table 3.3 Sediment deposition at Lake Yarrunga between 2003 and 2014. Volumes were estimated using the average area of consecutive cross-sections multiplied by the length distance

Cross-section	Depositional area (m^2)	Average area (m^2)	Length (m)	Volume (x 10^3 m^3)
1	38	85	1,250	106
2	132	93	510	47
3	54	63	570	36
4	72	63	1,000	63
5	54	88	550	48
6	122	118	1,800	212
7	114	79	1,800	142
8	44	113	1,760	199
9	182	165	1,100	181
10	148	318	570	181
11	488	380	320	122
12	272			
13	190	137	1,005	138
14	84	172	832	1,438
15	260	275	633	1,748
16	290	401	450	1,808
17	512	280	423	1,188
18	48	61	443	278
19	74	83	600	50
20	92	59	2,130	126
21	26	92	1,067	98
22	158	205	1,373	281
23	252	251	772	194
24	250	223	770	172
25	197	243	768	187
26	290	284	997	283
27	278	208	1,722	358
28	138	114	1,529	174
29	90	94	1,620	152
30	98	87	1,424	124
31	76	76	1,190	90
32	76	74	1,100	81
33	72			
34	154	153	227	35
35	152	151	442	67
36	150	165	287	47
37	180	131	287	38
38	82	52	288	15
39	22			

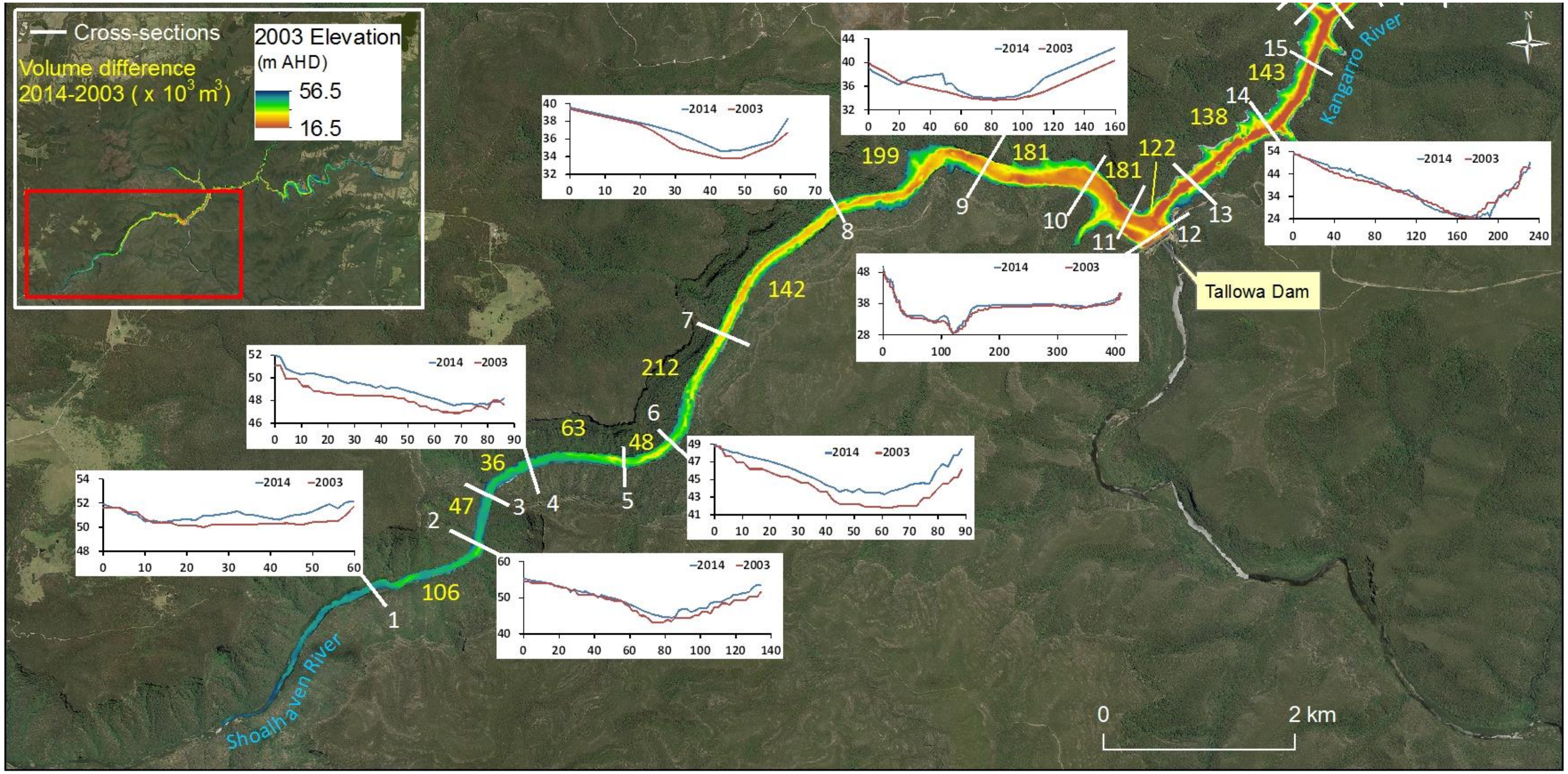


Figure 3.4 Sediment deposition on the western side of Tallowa Dam showing 2003 elevation provided by Sydney Catchment Authority. Cross-sections are plotted in white, whereas volumes of deposition (x 10^3 m^3) between 2003 and 2014 are shown in yellow. Sediment deposition at individual cross-sections was calculated using the areal difference between 2014 and 2003 cross-sections, and volumes were estimated using the average area of consecutive cross-sections multiplied by the distance between them (Table 3.3). Due to space restrictions, only a few selected graphics with 2003 (red) and 2014 (blue) cross-sections are shown. Note the different x and y axis scales between plots. Background imagery © NSW Government. Land and Property Information (LPI) 2013; Bathymetric data © Sydney Catchment Authority (SCA) 2014.

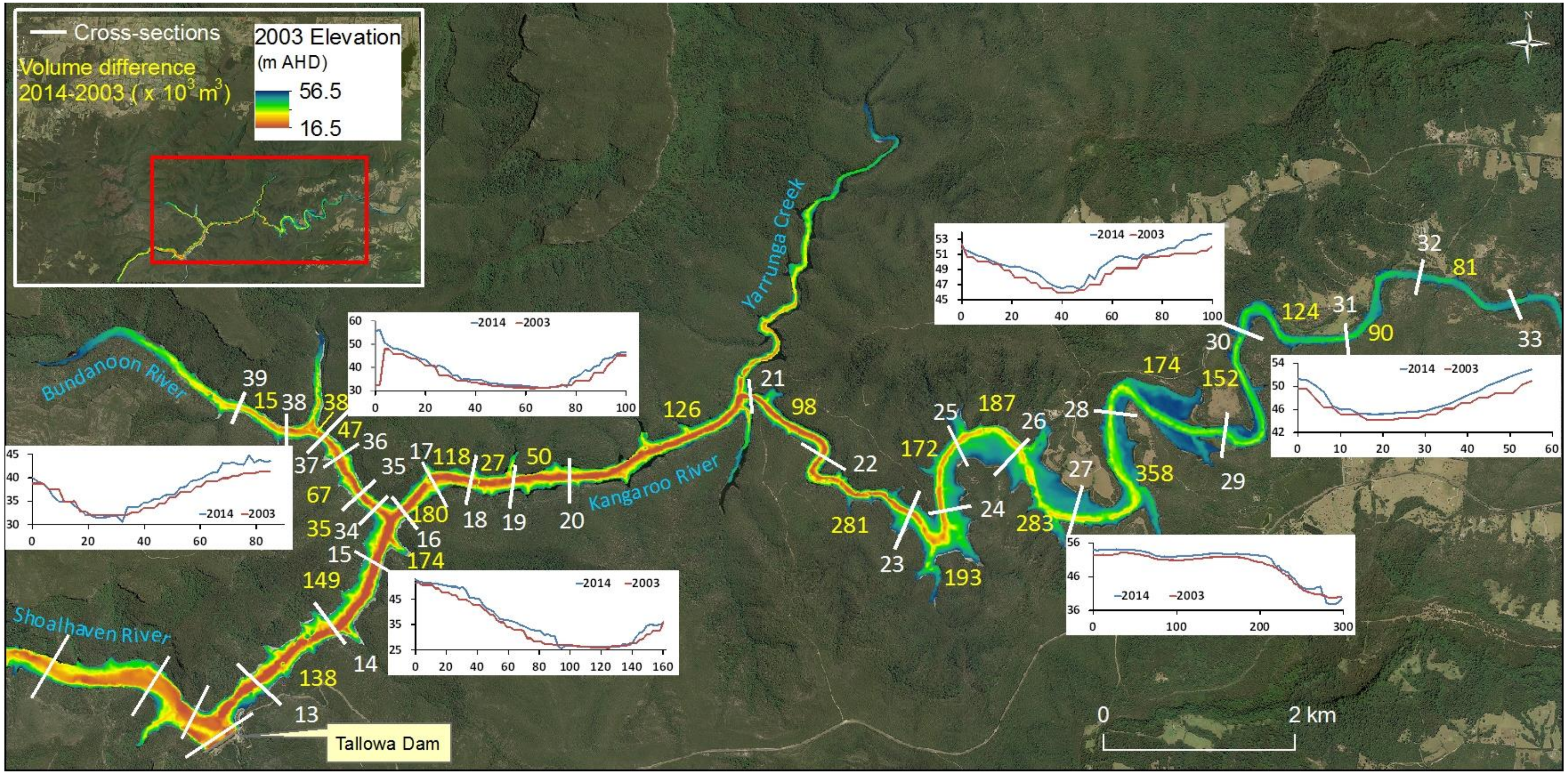


Figure 3.5 Sediment deposition on the eastern side of Tallowa Dam showing 2003 elevation provided by Sydney Catchment Authority. Cross-sections are plotted in white, whereas volumes of deposition (x 10^3 m^3) between 2003 and 2014 are shown in yellow. Sediment deposition at individual cross-sections was calculated using the areal difference between 2014 and 2003 cross-sections, and volumes were estimated using the average area of consecutive cross-sections multiplied by the distance between them (Table 3.3). Due to space restrictions, only a few selected graphics with 2003 (red) and 2014 (blue) cross-sections are shown. Note the different x and y axis scales between plots. Background imagery © NSW Government. Land and Property Information (LPI) 2013; Bathymetric data © Sydney Catchment Authority (SCA) 2014.

This can be explained by three facts: the first is related to the geology-geomorphology of the middle Shoalhaven catchment, dominated by an undulating surface of low relief of 600-700 m altitude, where a number of the catchment streams have been dammed by basalt flows (Nott, 1992). This area, named the Shoalhaven Plain by Craft (1931) is characterised by irregularly spaced pockets of floodplain confined by bedrock at both its upstream and downstream ends, in a ‘beads on a string’ configuration, as a consequence of its faulting history, and acts as a sediment storage zone (Johnston and Brierley, 2006). It consists of a sequence of wedged-shaped deposits that thin notably down valley, and have been described in highland catchments of southeastern Australia (Prosser et al., 1994, Johnston and Brierley, 2006). In fact, according to Nott (1990), the middle and upper Shoalhaven catchment contains probably the largest body of alluvium (area superior to 2,000 km^2) of any catchment in southeastern Australia.

Besides the sediment trapping in the Shoalhaven Plain, further downstream, the vegetation covers almost entirely the sub-catchments (both tributaries and main channel) that discharge on the western side of Lake Yarrunga (Figure 3.2). The dense vegetation covers not only the flatter areas but also the steep slopes of the Shoalhaven gorge and is believed to reduce the physical erosive effects upon this part of the Shoalhaven catchment. On the other hand, a large part of the Kangaroo River catchment is covered by pasture, which is known to produce between 3.8 and 27 times more sediment than native forest in the Tablelands of NSW (Neil and Fogarty, 1991, Mahmoudzadeh et al., 2002).

The third fact that explains the higher yields of the sub-catchments on the eastern side of Lake Yarrunga is the amount of rain that falls. Taking the 2011 calendar year (Figure 3.3), described by Carvalho and Woodroffe (2015) as an average year of rainfall for the Shoalhaven catchment, as an example, it is clear that the rainfall in parts of the Kangaroo River catchment is up to three times more than the rain that falls in other parts of the Shoalhaven catchment, especially on the western side.

The other major consequence for the sediments deposited in Lake Yarrunga, and of major implication for the sediment budget in the Shoalhaven coastal compartment is that it can be used to validate the sediment yield calculated using the 88 % of trap efficiency calculated for Tallowa Dam by Boyd et al. (1977) using Brune’s (1953) capacity–inflow ratio.

If 88 % of the sediment yield by the upstream catchments corresponds to an average volume deposition at the dam site of 465,000 m^3/y, the average sediment yield for the catchments upstream from Tallowa Dam equals approximately 528,000 m^3/y. Of that amount, approximately 143,000 m^3/y comes from the catchments that discharge in the western part of Lake Yarrunga and 385,000 m^3/y from the catchments in the eastern part. The average volume of 528,000 m^3/y is much less than the sediment yield at the dam site of 1,380,000 tonnes/y (897,000 m^3/y) calculated by Boyd et al. (1977) and much more than the 100,000 m^3/y of sediment supply from the whole catchment calculated by DPW (1977).

Summing up the sediment yields of the upstream catchments (1 to 22) draining to Lake Yarrunga using the Langbein and Schumm method during 2011 and presented in Table 3.1, a value of 745,322 tonnes is derived. Multiplying by 0.65, a volume of 484,459.3 m^3 is obtained. At a first glance this value obtained by using the Langbein and Schumm relationship is not far-off from the 528,000 m^3/y calculated using the volume of sediments deposited in the dam. However, a closer look into the sediment yields for the upstream catchments that discharge into the western (catchments 1-20) and eastern (catchments 21-22) side of the dam, provides values of 708,154 tonnes and 37,168 tonnes, which is equivalent to 460,300 m^3 and 24,159 m^3, respectively. These are very different figures from the 143,000 m^3/y and 385,000 m^3/y that were calculated using the volume deposited at Tallowa Dam.

Therefore, despite providing similar annual sediment yields for the catchments upstream from the dam site, the use of Langbein and Schumm (1958) method provided completely inconsistent results for the sub-catchment yields. The reasons for this lie in the simplicity and limitations of the method based on data from the USA described earlier. In fact, the application of models developed for use in mid to high latitude rivers in the northern hemisphere to estimate bedload yields for coastal rivers in Australia has been described as a futile exercise, with enormous variation and no recognizable continuity of results (Hean and Nanson, 1987).

The assertion by Hean and Nanson (1987) has been supported by the work of Brooks et al. (2014), who used the Revised Universal Soil Loss Equation (RUSLE) in northern Queensland and concluded that the model over predicted the results between 12 and 13,300 times; and the work of Simms (2007), who concluded that even the version of the Universal Soil Loss Equation (USLE) modified to incorporate spatial-temporal variations in coastal catchments of the Sydney Basin (OzMUSLE) might not be a useful tool for assessing sediment delivery at the catchment scale until further refinement and testing is carried out. Simms (2007) calculated that annual average rates of soil loss for Lake Wollumboola and Cordeaux catchments were 0.46 t/ha/y and 0.17 t/ha/y respectively, which are considered low to insignificant values in relation to soil formation rates and sediment yields using excess lead-210 ($^{210}Pb_{ex}$).

The reasons behind these errors of calculated yields might be associated with severe limitations of sediment supply, as a result of extremely low rates of denudation in the form of upland lowering, major escarpment retreat and interfluve consumption experienced in the eastern highlands of Australia (Young, 1983, Nott et al., 1996) or the fact that the USLE/RUSLE models were developed to estimate erosion on plots that were uniform in relation to soil and land cover (Simms, 2007). Nevertheless, the values of somewhere between 7,300 and 73,000 m^3/y calculated for the Shoalhaven catchment by Hubble (1998) based on geological evidence provided by Nott et al. (1996) seem to be underpredicting yields.

3.6 Sediment yield downstream from Tallowa Dam

Once escaped from the dam, 63,000 m^3/y of sediment on average becomes available for the coastal budget, but before reaching the estuary at Burrier, the sediment has to be transported through a series of pools and riffles found in the 25 km freshwater reach upstream of the tidal limit. It is unlikely that a great amount of sediment settles in the pools and riffles, since the pools are relatively shallow (mean maximum depth of 6.5 m) and riffles are formed primarily of alluvial cobbles and gravels (Reinfelds and Williams, 2012).

Approximately 13 km downstream from Tallowa Dam, a major tributary discharges at the Shoalhaven main stream. This tributary, represented by sub-catchment 26 in Figure 2.1, is formed by the confluence of sub-catchments 24 (Ettrema Creek) and 25 (Boolijah Creek).

The total area of sub-catchments 24, 25 and 26 combined is more than 700 km^2, approximately 10 % of the total Shoalhaven Catchment area. These sub-catchments have slopes (Figure 3.2) and rainfall regimes (Figure 3.3) similar to Bundanoon Creek (sub-catchment 21) that discharges into Lake Yarrunga and their combined area is about twice the size of Bundanoon Creek sub-catchment (319 km^2), despite being almost entirely covered with forest. Since no reliable sediment yield calculation for these sub-catchments can be made, an estimation of a similar value of the annual volume delivered from Bundanoon Creek to Tallowa Dam is assumed.

Bundanoon Creek deposited an estimated 227,801 m^3 of sediments into Lake Yarrunga between 2003 and 2014, a rate of approximately 20,000 m^3/y, that added to an extra 12 % of sediments not trapped by the dam, equals approximately 23,000 m^3/y. Therefore, this is assumed as the contribution of the catchments downstream from Tallowa Dam

The total sediment yield from the Shoalhaven River in the past 40 years, since the construction of Tallowa Dam, is the sum of 63,000 m^3/y and 23,000 m^3/y. An estimated average of 86,000 m^3/y that incorporates extremes (floods), as well as prevailing conditions.

3.7 Summary

Four fluvial systems discharge into the Shoalhaven coastal compartment. The Shoalhaven River and the Crooked River discharge into the Seven Mile Beach-Comerong Island tertiary level compartment, whereas the Coonemia and Currarong creeks discharge into the Warrain-Currarong tertiary level compartment. No major system discharges into Culburra.

The Shoalhaven catchment is by far the most important fluvial system of the Shoalhaven coastal compartment with a catchment area of more than 7,000 km^2. The river crosses two major geologic provinces. The upper and middle catchment lie across the Palaeozoic Lachlan Fold Belt, whereas the lower section is incised through the southern Sydney Basin. The main stream of the catchment is 340 km long and after crossing a low relief terrain in the middle catchment, has carved steep-sided gorges, before reaching the Holocene deltaic-estuarine plains. The headwaters reach approximately 1,400 m but only 11 % of the total area is located above 750 m of altitude. Nine soils types occur underneath mainly forest and pasture lands.

Most of the sediment yield by the catchment is believed to be trapped at Lake Yarrunga, formed after the construction of Tallowa Dam (catchment area of 5,631 km^2) in 1976. It has been calculated that more than 5,100,000 m^3 was deposited in the lake between 2003 and 2014, which provides an average annual catchment yield above the dam site of approximately 528,000 m^3, with less than 30 % of the volume provided by the catchments that discharge on the western part of the lake.

The 12 % of the sediments calculated by Boyd et al. (1977) that escape being trapped by the dam, corresponds to an estimated 63,000 m^3/y of sediments approximately that becomes available to the sediment budget downstream. Due to the inefficiency of models to estimate bedload yields applied to the Australian context, sediment yields downstream from the dam could only be estimated based on similarities, such as catchment area, slope and rainfall regime. The total sediment yield from the Shoalhaven River in the 40 years, since the construction of Tallowa Dam corresponds to a volume of 86,000 m^3/y. This figure sets the baseline for the sediment budget as the river is the most important feature of the Shoalhaven coastal compartment.

The Crooked River has a stream that flows for 8 km before forming a small barrier estuary at Gerroa and a catchment area of approximately 30 km^2, same size as the Coonemia Creek catchment. This creek forms a saline coastal lagoon, near Warrain. Currarong Creek, located further south, drains an even smaller catchment of approximately 12 km^2 that discharges at Currarong. Based on catchment sizes, fluvial sediment yield for these three catchment to the coast is considered negligible.

Chapter 4: Estuarine systems

This chapter contains the results and discussion of the data analyses for both major estuarine systems in the Shoalhaven coastal compartment. An introduction to the Shoalhaven estuary and Lake Wollumboola is given first. After that, information about both estuarine morphologies is provided. Then, subsequent sections about the Shoalhaven estuary investigate the volumetric changes, the dynamics of Shoalhaven Heads during breaching events, the extent and mechanisms of bank erosion, the texture, shape and mineralogy of the estuarine sediments, and in-channel bedforms.

The first two sections were designed to provide a morphometric comparison between the two estuaries that connect the Shoalhaven River and the Coonemia Creek to the northernmost and southernmost tertiary level compartments, respectively. The remaining sections were designed to provide information that will be used to estimate volumes of estuarine deposition, erosion and extraction of sediments by mining activities in the Shoalhaven estuary, as well as to understand exchanges of estuarine sediments to the nearshore of Seven Mile Beach-Comerong Island tertiary level compartment.

4.1 Introduction

The Shoalhaven estuary is a wave-dominated barrier estuary (Roy et al., 1980, 2001), which occupies a drowned valley constricted by flood tidal deltas and impounded by a coastal sand barrier. Like many barrier estuaries, the Shoalhaven is characterised by estuarine and fluvial depositional environments, with extensive subaqueous "mud basin" deposits that interdigitate with fluvial deltaic sediments in a landward direction, and with tidal deltaic sand bodies in a seaward direction.

The Quaternary plain of the Shoalhaven River is an example of a mature stage estuary (Roy et al., 2001). Under low-flow conditions, full tidal effects are able to penetrate into the estuary resulting in a well-mixed estuary (Wright, 1977). Well to partially-mixed conditions occur in the lower reaches of both entrances, with marine salinities prevailing immediately upstream of Shoalhaven Heads and then decreasing progressively until surface salinity becomes fresh at 12-15 km upstream from Shoalhaven Heads (Wright et al., 1980). During flood events, salt water is completely flushed from both entrances despite tidal rising and falling within the lower reaches of the Shoalhaven Heads channel (Wright, 1977).

Tides are semidiurnal with a mean range of 1.2 m (spring range of 1.8 m) and their influence extends approximately 20 km upstream until Burrier. The tidal prism of the estuary is approximately 23 x 10^6 m^3 during spring tide, which exceeds the base flow by 18 times, but represents only 20 % of the extreme flood discharge volume (Wright et al., 1980). A low stream gradient, relatively large tidal prism, and low base flow, results in seawards sediment discharge only during flood events when seawater is flushed from the estuary, bed shear stresses are large and bedload transport occurs due to the presence of seaward-migrating channel bedforms at Shoalhaven Heads (Wright et al., 1980).

Although the Shoalhaven River mouth is breached during floods, most of the time the normal flow is diverted through an artificially dug 200-m long canal, constructed in 1822 (Berrys Canal) forming Comerong island, and only reaches the ocean at Crookhaven Heads (Young et al., 1996, Umitsu et al., 2001). Since then, Berrys Canal continues to widen (PWD, 1988, Woodroffe et al., 2000, Thompson, 2012) and directs the flow of the Shoalhaven River to exit at Crookhaven Heads.

The former mouth of the river at Shoalhaven Heads has been impounded by the deposition of a sandy berm, as a result of the consequent reduction in riverine flow. Following major floods, the outlet is breached temporarily while the river flows naturally to the Tasman Sea, with the beach berm gradually re-establishing over time. Past analysis of breached time and entrance modification were conducted by DPW (1977), Chafer (1998) and Carvalho and Woodroffe (2013). In the past two decades this breaching was only achieved mechanically via human interference, as an emergency procedure, by the Shoalhaven City Council, following the Entrance Management Policy for Shoalhaven Heads (Shoalhaven City Council, 2006), recommended by the HRC (1999) guidelines for floods risks.

The construction of Tallowa Dam, upstream of Nowra, in 1976, represents another major modification to the catchment impacting the Shoalhaven estuary. Lake Yarrunga, the reservoir formed to transfer water to Sydney, has a maximum operational capacity of 35 GL (Reinfelds and Williams, 2012), smoothing the flash flooding of the river considerably (Short and Woodroffe, 2009), increasing the salinity (approximately

3 ppt) in the middle estuary (Miller et al., 2006) and reducing the sediment delivery (Boyd et al., 1977).

The geomorphology of the deltaic-estuarine plains of the Shoalhaven River was studied by Thom et al. (1981), Young et al. (1996), Woodroffe et al. (2000) and Umitsu et al. (2001). The cited works provide a detailed description of fluvial deposition, estuarine infill, formation and Holocene palaeoecology of the lower end of the Shoalhaven. Thom et al. (1981) suggested the gradual estuarine infill of Shoalhaven based upon a west-east transect of five drillholes. Young et al. (1996) showed that the plains are Holocene, overlying Pleistocene alluvium, composed of two superimposed units from different provenances determined by radiocarbon dating. Woodroffe et al. (2000), through extensive drilling, showed that most of the estuarine infill occurred 5500-3500 radiocarbon years BP and, thereafter, a transition from brackish water to freshwater conditions occurred. These authors found marine sand deposited behind the barrier-system and estuarine muds with a brackish-water molluscan assemblage throughout the plains. Umitsu et al. (2001) provided a chronology of mid-Holocene ecological changes on the plains, expanding the findings of Woodroffe et al. (2000) and showing that there are extensive potential acid sulphate soil conditions beneath the plains.

Erosion along the riverbanks of the Shoalhaven estuary between Nowra Bridge and Crookhaven Heads and Shoalhaven Heads was first studied by PWD (1988). Then, Nolan (1997) studied the erosion occurring in the 30 km upstream from the bridge. Patterson Britton and Partners (2004) carried out field inspections in the whole estuary to identify sections of the bank and determined potential bank restoration measures, and more recently, Glamore and Davey (2013) assessed riverbank vulnerability for the 22.3 km section of the estuary upstream from the Nowra bridge.

Lake Wollumboola located south of Culburra is considered a saline coastal lagoon, a member of the intermittently-closed estuaries group of Roy et al., (2001). This group refers to coastal water bodies that occur in similar settings to barrier estuaries in south-eastern Australia. However, due to their small catchments and river discharges, saline coastal lagoons become isolated from the sea for extended periods of time (Roy, 1984). Lake Wollumboola is, therefore, non-tidal for long periods and only during storm waves and/or raised water levels is the beach berm south of Warrain breached.

Sediment distribution and rates of accumulation across Lake Wollumboola have been studied by Umwelt (1999) and Baumber (2001). The former identified marine sands as back-barrier and tidal delta deposits along the eastern side of the lake, fluvial sediments deposited at the mouth of the creeks located on the western side, and a black ooze present across much of the central mud basin. The latter applied radiocarbon and ^{210}Pb dating to determine recent sedimentation rates in the mud basin and at the fluvial deltas. Baumber's (2001) radiocarbon dating results indicated sedimentation centred in the mud basin of less than 1 mm/y, whereas records of sedimentation provided by ^{210}Pb dating indicated a rate of over 3 mm/y for the fluvial delta.

4.2 Estuarine morphologies

The Shoalhaven estuary extends for approximately 46 km from the Shoalhaven Heads entrance to the tidal limit at Burrier (Figure 4.1). Despite being considered a barrier estuary, the Shoalhaven estuary is not typically flat-bottomed, and estuarine water reaches almost twice the depths of typical 'type 2' estuaries described by Roy et al. (1980). Maximum in-channel depth reaches 21.4 m below AHD in a hydraulic pool located 750 m upstream from Nowra Bridge. Other deep areas below 15 m include eight hydraulic pools upstream from the bridge and only one downstream, at Berrys Canal.

The total accommodation space for the Shoalhaven estuary, also known as the estuarine volume below 0 m AHD available for sediment deposition, is approximately 55.4 x 10^6 m^3. The hypsometric curve calculated for the estuarine area downstream of Burrier (~23 km^2), depicted in Figure 4.1, shows that most of the estuary is very shallow. Less than 2 % of the total estuarine area is deeper than 10 m. Approximately 10 % of the area is deeper than 5 m. More than 50 % of its area is shallower than 2 m and about 80 % is shallower than 0.5 m. This confined accommodation space restricts the deposition of fluvial sediments in the estuary favouring the transport of catchment-derived sediments to the coast.

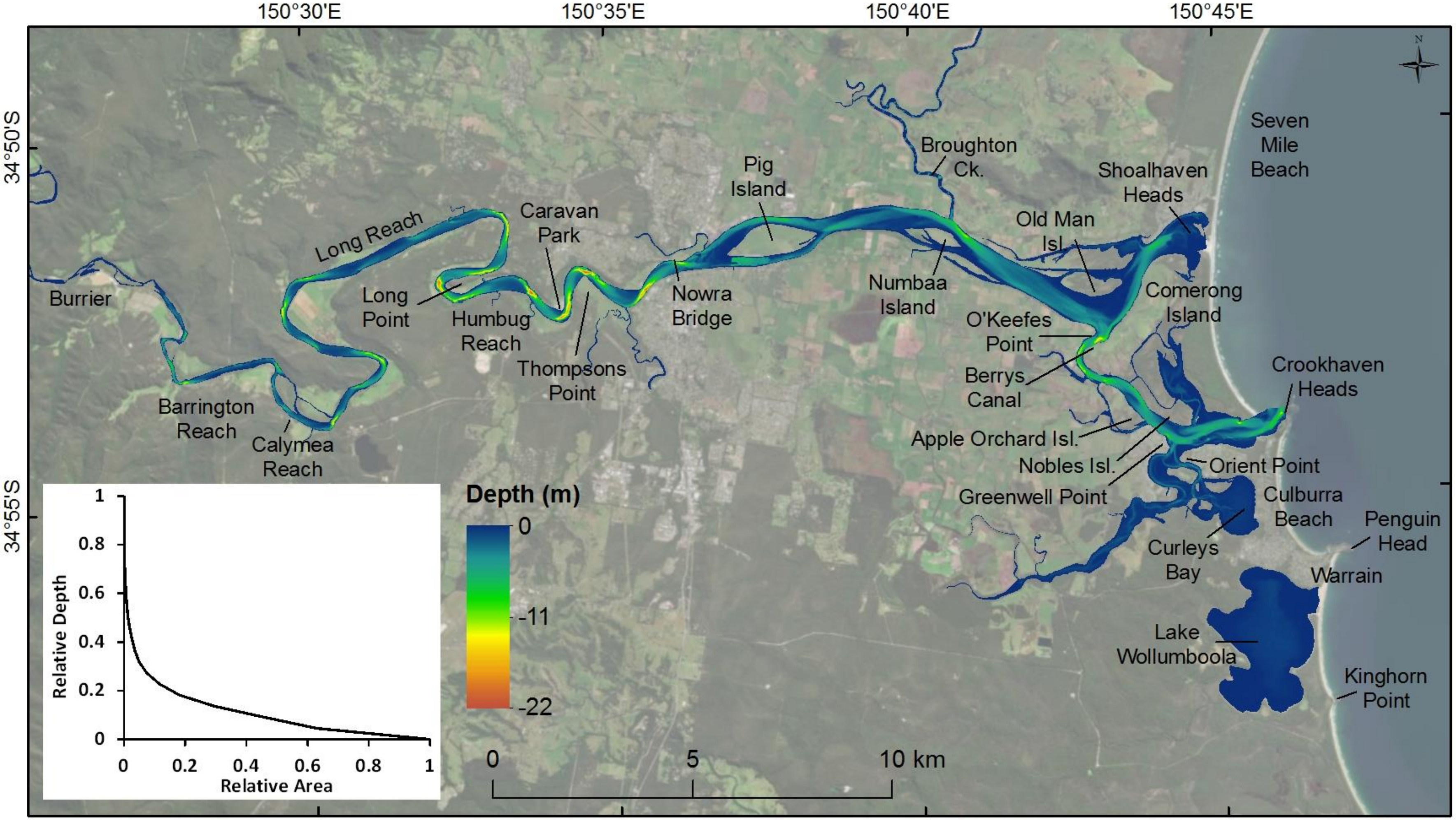


Figure 4.1 Bathymetry of the Shoalhaven estuary in 2006 and Lake Wollumboola in 1991. Hypsometric curve (Dimensionless x and y axis) for the Shoalhaven estuary located on the left corner. Important locations mentioned in text are labelled. Bathymetric data © NSW Government. Office of Environment and Heritage (OEH) 2006 and 1991. Background imagery © LP DAAC.

Lake Wollumboola located south of Culburra occupies an area of approximately 6.5 km^2 (Figure 4.2). This saline coastal lagoon is very shallow (maximum depths of 1.1 m) and estuarine volume below 0 m AHD available for sediment deposition, is approximately 1.9 x 10^6 m^3. The hypsometric curve shows that approximately 50 % of the area is shallower that 0.4 m and that depths within the lake are much more equally distributed in terms of area than the Shoalhaven estuary (Figure 4.1).

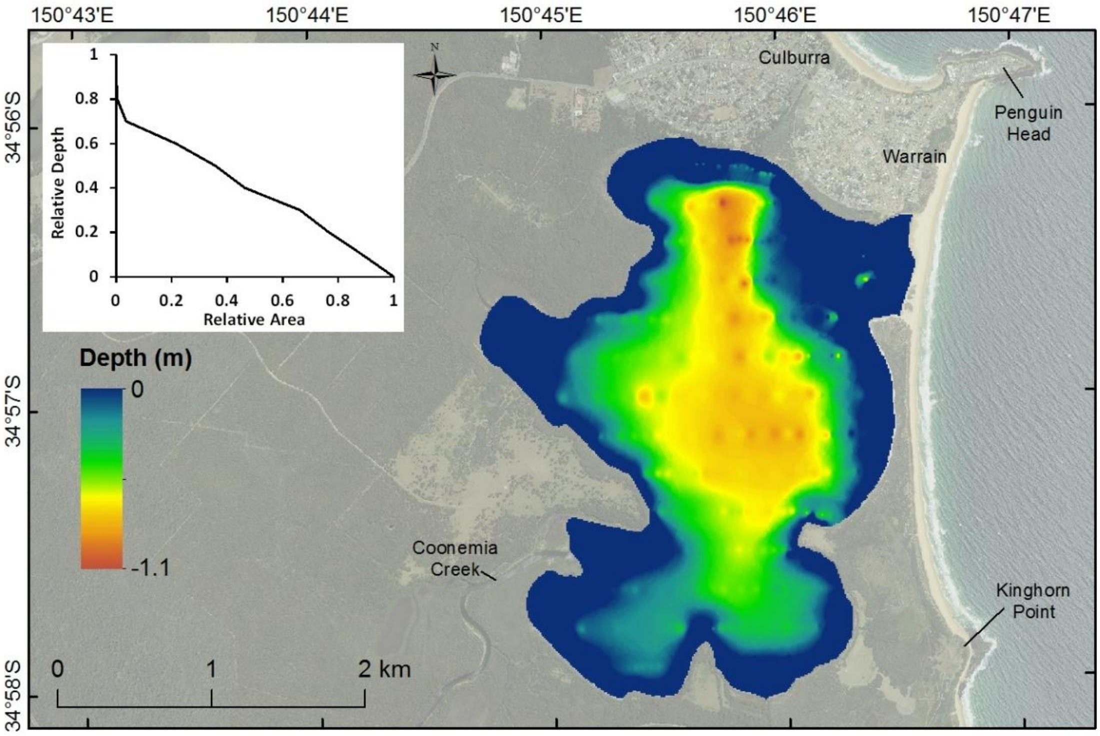


Figure 4.2 Bathymetry and hypsometric curve (Dimensionless x and y axis) of Lake Wollumboola in 1991. Important locations mentioned in text are labelled. Bathymetric data © NSW Government. Office of Environment and Heritage (OEH) 1991. Background imagery © NSW Government. Land and Property Information (LPI) 2013

4.3 Volumetric changes in the Shoalhaven estuary

Volumetric changes experienced in the Shoalhaven estuary are better understood by looking at the depth modifications that occurred between 1981 and 2006. Approximately 400,000 m^3 of sediment was deposited throughout most of the estuary (from Long Reach to both Shoalhaven Heads and Crookhaven Heads entrances- the area covered in the 1981 survey) over the 25-year period. However, dividing the area in two, just upstream of O'Keefes Point, it was observed that the upper part (Figure 4.3) accreted approximately 2,000,000 m^3, whereas the lower part eroded approximately

1,600,000 m^3, showing that a lot of fluvial deposition occurred upstream of O'Keefes Point, and that erosion heavily dominated between the two entrances.

The first survey, carried out in 1981, registered a maximum depth of 21.6 m. 0.2 m deeper than the maximum depth recorded in the 2006 survey. The map on the bottom of Figure 4.3 shows the areas where deposition and erosion occurred between 1981 and 2006. Areas of substantial deposition higher than 4 m, represented by dark blue, were located mostly upstream from Nowra, but areas with vertical deposition of up to 2 m were found throughout the estuary. Areas of erosion mostly occurred along the estuarine channel, especially on the north of Pig and Numbaa Islands, as well as at some pools upstream from Nowra (dark red). Downstream from Numbaa Island, the estuarine thalweg migrated towards the right margin, as indicated by the light red channel.

An area of approximately 200,000 m^2 located on the southwest of Pig Island was excavated for sand mining and depth increased 7.5 m in some points. A volume of approximately 620,000 m^3 was extracted between the two surveys. When this value is added to the 2,000,000 m^3 calculated previously, a total estuarine deposition of 1,020,000 m^3 (2,620,000 m^3 - 1,600,000 m^3) is inferred between 1981 and 2006.

In the lower part of the estuary (Figure 4.4), between Shoalhaven Heads and Crookhaven Heads, the first survey carried out in 1981 showed a maximum depth of 15.6 m in Berrys Canal, opposite to O'Keefes Point. At Crookhaven Heads, the channel reached 7.2 m depth on the southern flank of the estuary, near Orient Point, and a maximum depth of 12.9 m near the training walls, further downstream. A cross-channel sand bar deposit intersected the meandering channel and shallow depths of 3.9 m were observed there. The channel towards Shoalhaven Heads reached 8.5 m deep but it shallowed out to less than 1 m about 700 m before the beach.

The survey carried out in 1989 only covered the downstream part of the natural channel that leads to Shoalhaven Heads. Maximum surveyed depth was 7.7 m and a 100 m wide channel of 1 m depth existed connecting the estuary to the beach. Compared to the same area 8 years prior, Shoalhaven Heads lost approximately 160,000 m^3 of sediments, explained by the fact that in July/1988 Shoalhaven Heads was breached and the sediment was flushed to the nearshore.

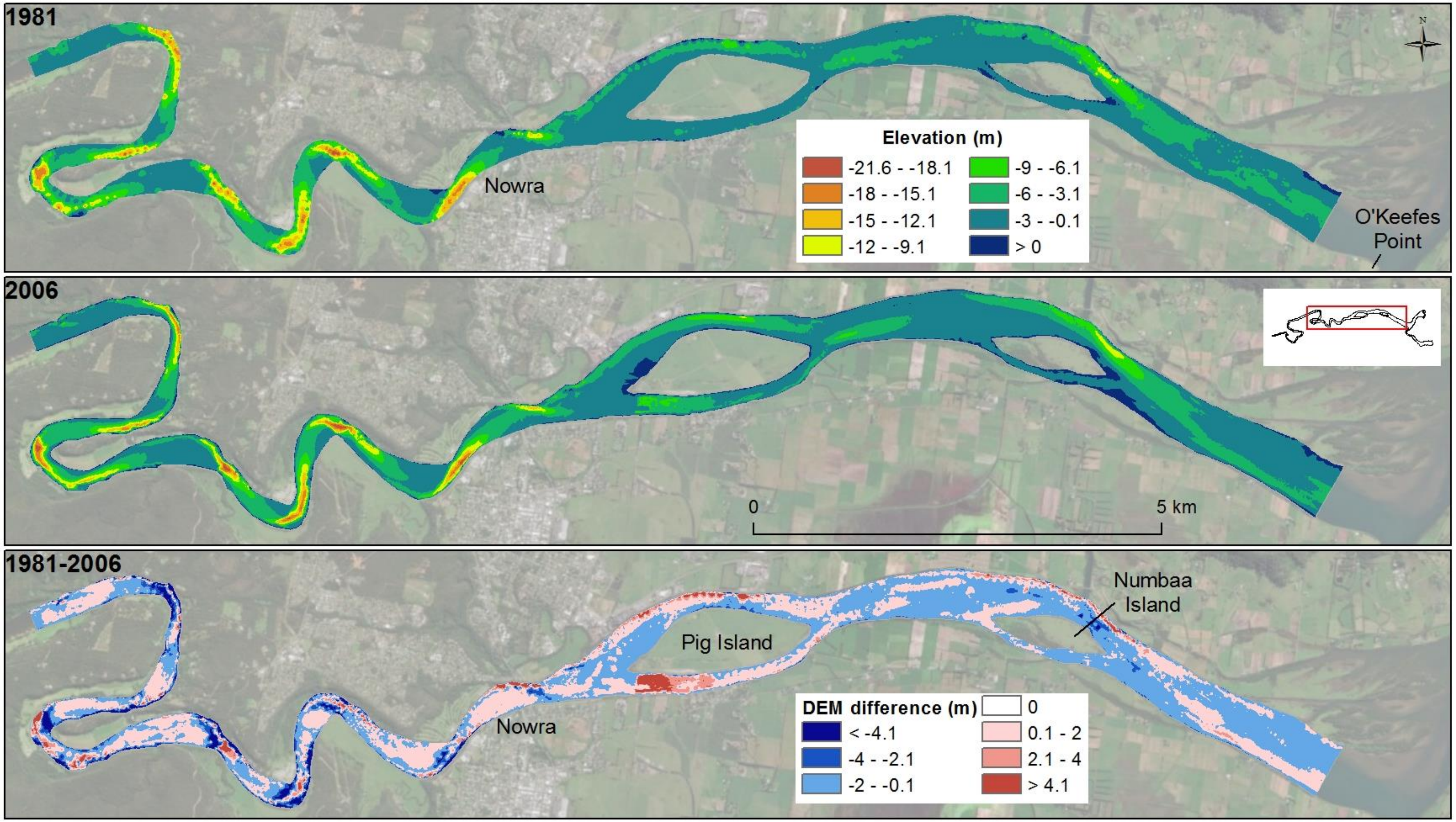


Figure 4.3 Bathymetric variation in the Shoalhaven estuary between Long Reach and O'Keefes Point in 1981 and 2006. In the lower map, red polygons indicate areas where erosion occurred whereas blue polygons indicate areas of accretion over time. Bathymetric data © NSW Government. Office of Environment and Heritage (OEH) 2006. Background imagery © NSW Government. Land and Property Information (LPI) 2013

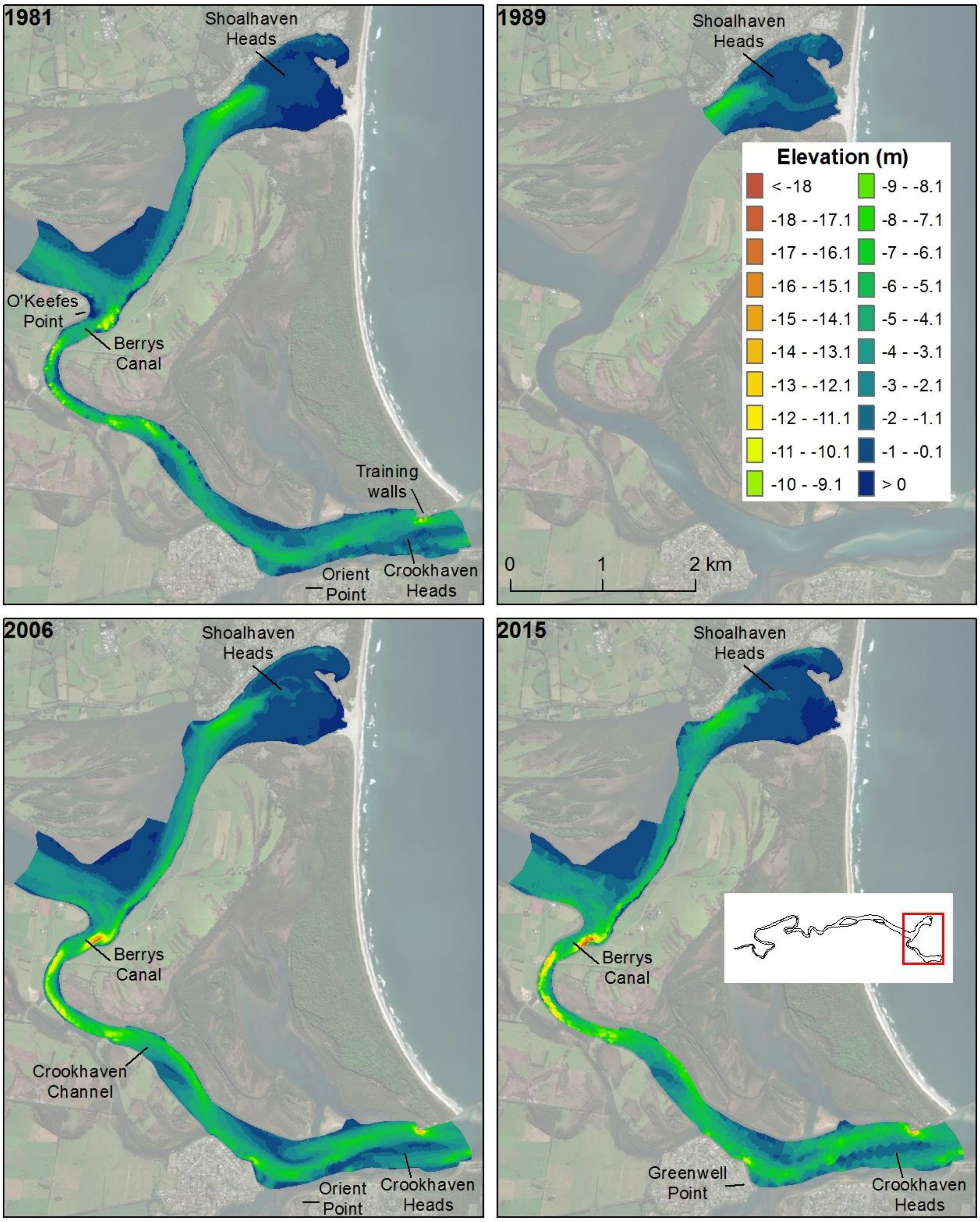


Figure 4.4 Bathymetric variation at the lower end of the estuary between Shoalhaven Heads and Crookhaven Heads since 1981. Bathymetric data except 2015 © NSW Government. Office of Environment and Heritage (OEH) 2006. Background imagery © NSW Government. Land and Property Information (LPI) 2013

In 2006, the detailed bathymetry between both entrances showed a deeper Crookhaven channel, reaching maximum depth of 17.8 m at Berrys Canal, 2.3 m deeper than the maximum depth recorded in 1981. Compared to the 1989 survey, the 2006 survey showed that at Shoalhaven Heads the old existing channel located in the south had disappeared, a new channel developed in the north and deposition also occurred near the northern shoreline. A comparison of the interpolated data gave an estimate of 284,890 m^3 of sand accumulated over the 17-year interval, implying an average rate of 16,760 m^3/y. This accumulation rate is limited by three facts: i) Shoalhaven Heads was closing in 1989 from the breaching event that happened in middle 1988; ii) another major event opened up Shoalhaven Heads in the middle of 1990, taking 3.5 years to close; and iii) much weaker breaching events that occurred in 1989-1999.

Regarding the Crookhaven Heads entrance, the meandering pattern of the thalweg remained the same in 2006, when compared to the 1981 survey, but maximum depths increased to 10.2 m on the southern flank, near Orient Point, 4.5 m in the cross-channel sand bar, and 15 m on the northern flank, near the training walls.

The bathymetric campaign carried out specifically for this project in 2015 showed a very similar pattern as in 2006, with minor changes in the morphology but considerable changes in volume of sediments. Regarding the entire area surveyed in 2015, a net volume loss of approximately 1,095,000 m^3 occurred between 2006 and 2015, which corresponds to an average loss of 122,000 m^3/y. However, not everywhere behaved the same way.

The channel that existed in 2006 at Shoalhaven Heads, was still observed in 2015, but was encountered further away from the beach. Deposition continued and an extra volume of approximately 61,000 m^3 of sediments accumulated over the nine-year interval, an average rate of 6,780 m^3/y, using the polygonal area of the 1989 survey. This lower accretion rate than the one estimated between 1989 and 2006 may be partly explained by the fact that Shoalhaven Heads remained open for eight months after the breaching event in June/2013, and some of the sediments deposited before the artificial opening are likely to have been transported offshore.

Towards Berrys Canal, maximum depths slightly increased to 18.1 m, but scouring took place near/downstream from the ferry crossing. Around Crookhaven Heads, not much change could be observed over the nine-year period, apart from the deepening of the channel itself to 11.3 m on the southern flank near Greenwell Point.

The difference in depths between DEMs derived from 1981, 1989, 2006 and 2015 surveys are shown in Figure 4.5. At Shoalhaven Heads, a loss of sediments was observed in most of the area between 1981 and 1989, driven by the breaching event that happened in 1988. Between 1989 and 2006, erosion occurred to form the new channel observed in 2006 and deposition was observed along most of the remaining area, reaching up to 3.4 m of accretion near the river mouth.

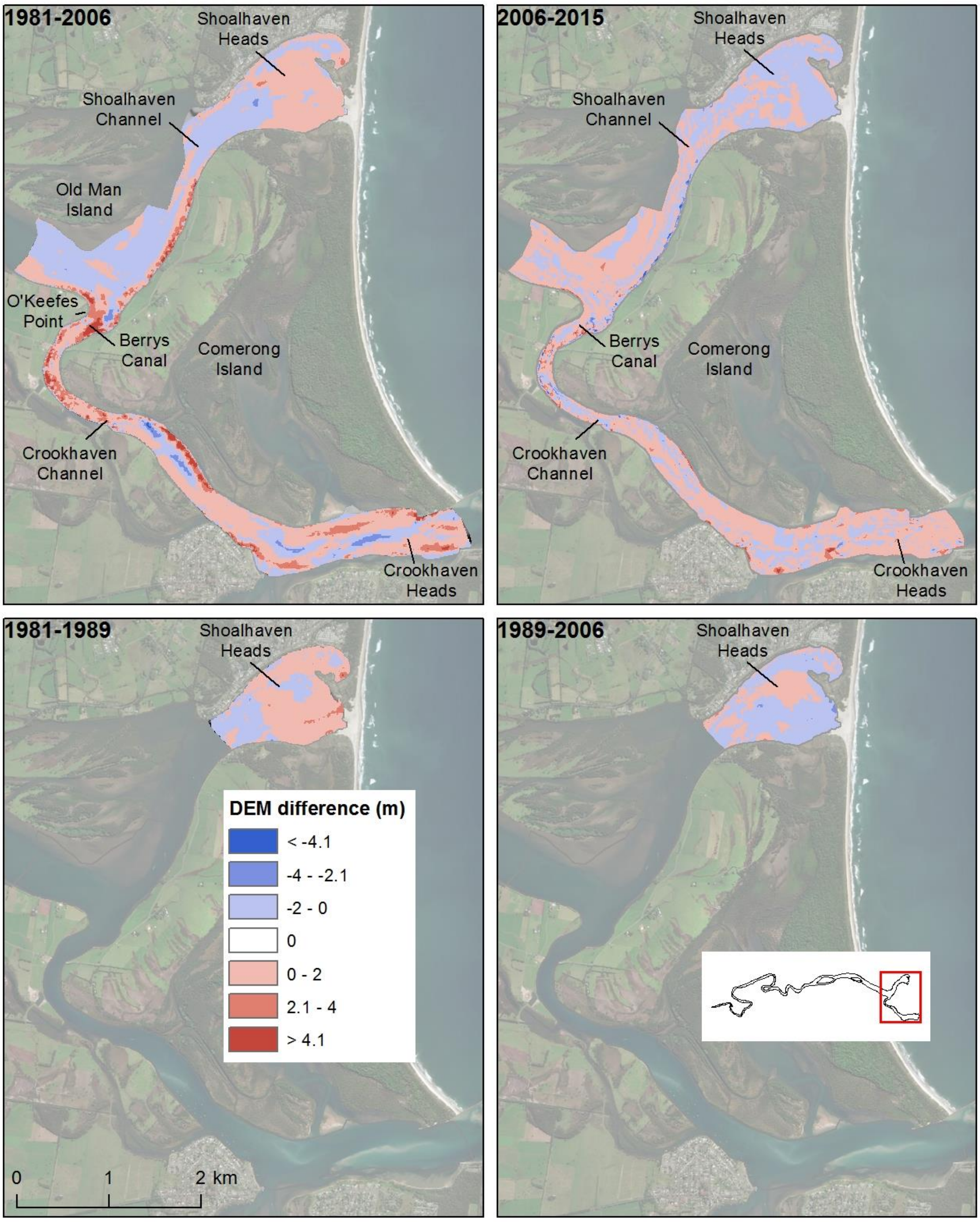


Figure 4.5 Bathymetric variation at the lower end of the estuary between Shoalhaven Heads and Crookhaven Heads. Red polygons indicate areas where erosion occurred whereas blue polygons indicate areas of accretion over time. Background imagery © NSW Government. Land and Property Information (LPI) 2013

A lot of deposition occurred near Old Man Island and towards Shoalhaven Heads between 1981 and 2006. However, erosion was predominant on the majority of Crookhaven channel, from O'Keefes Point to Crookhaven Heads. Heavy scouring took place along the entire Berrys Canal, several parts of Comerong Island and further downstream.

Between 2006 and 2015, deposition occurred mainly towards Shoalhaven Heads and consisted of less than 2 m of accretion, while, most of the area between Berrys Canal and Crookhaven Heads was dominated by less than 2 m of erosion. The Comerong Island side of the estuary, mainly towards Shoalhaven Heads, experienced most of the deposition of up to 5 m, whereas most of the deep eroded areas were located between Berrys Canal and Crookhaven Heads.

From the DEM difference maps, it is also inferred that erosion dominated most of the Crookhaven channel in the past 34 years, and that deposition is the major process happening along the Shoalhaven channel including Shoalhaven Heads, despite the gross losses that might occur during breaching events. This trend of erosion and deposition is apparent especially over longer periods such as between 1981 and 2006 and is expected as a result of the diversion of the flow via Berrys Canal and its continuing adjustment to fluvial and tidal scouring since 1822, and the low hydrodynamics experienced at Shoalhaven channel when Shoalhaven Heads is closed.

Some of the volumetric figures, as well as, the spatial extent of such changes over time, need to be addressed with caution as they represent an approximation calculated by the IDW interpolator used to generate the DEM of the bathymetric points.

4.4 Dynamics of Shoalhaven Heads

An analysis of aerial photographs and the Landsat imagery archive indicates that the river mouth at Shoalhaven Heads was open in 1961, 1974-1980, 1988-1994, twice in 1998-1999 and twice more through the course of this study: 2013-2014 and 2015-2016 (Figure 4.6). The oldest photo taken on 04/04/1949 shows the river mouth closed but the subsequent one, taken on 21/09/1961, is the first to register the breached outlet. The sand barrier was breached in the southern part, towards Comerong Island. The next aerial photograph showed a closed mouth and unfortunately was taken only on 16/04/1970, a long time-span in between records to determine how long it remained opened. However, information disclosed by Wright (1970) points to the existence of a narrow opening connecting Shoalhaven Heads to the sea in October 1965 and complete closing of the entrance by January 1966.

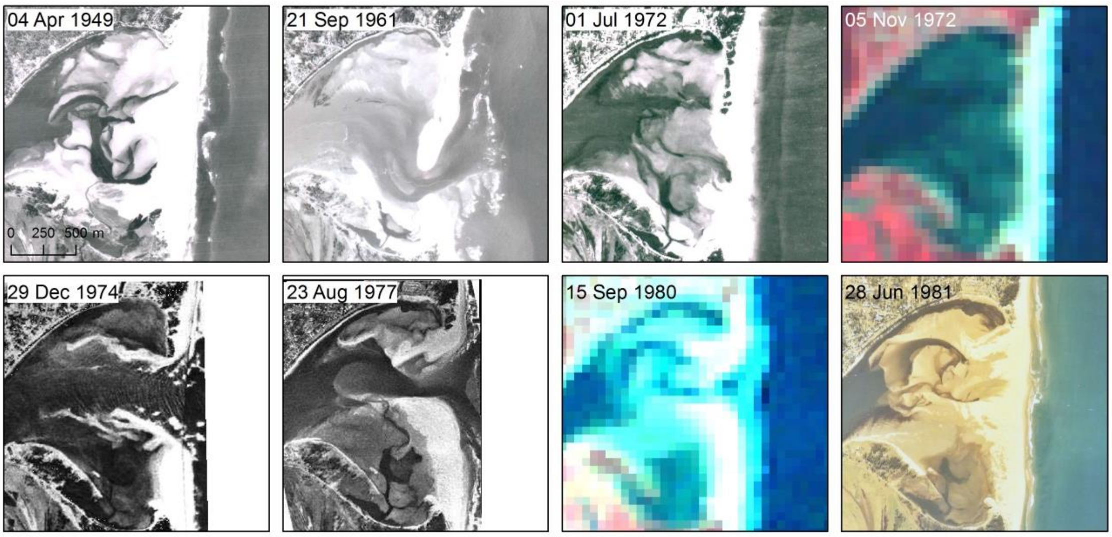


Figure 4.6 Selected historical aerial photographs and Landsat imagery (05/11/1972 and 15/09/1980) of Shoalhaven Heads showing morphologic conditions of the entrance between 1949 and 1981. Satellite imagery © LP DAAC.

Another photograph 37 days after the flight of 16/04/1970 still shows the deposition of sand widening the beach and deforming the concave shape of the Seven Mile Beach-Comerong Island embayment. Surf bars were also observed in the aerial photo taken on 23/05/1970.

The aerial photograph taken on 01/07/1972 shows that the action of the waves has transported sand and deposited it on the shoreline. A few months later, the first Landsat image capturing Shoalhaven Heads was acquired. The 05/11/1972 false-colour image shows the river mouth closed despite its low spatial resolution compared to the aerial photographs.

The effects of the storms of May-June 1974 (Bryant and Kidd, 1975, Foster et al., 1975, Lord and Kulmar, 2001) on the coast of NSW were apparent in the photo taken on 29/12/1974, which shows the approximately 700-m wide-open entrance. The Landsat 2 image and photos of late 70s and early 80s show the gradual closing of the entrance. The Landsat image of 15/09/1980 is the last to register the closing mouth, whereas the photograph taken on 12/02/1981 shows a completely closed entrance. The image taken on 28/06/1981, is the first colour aerial photograph capturing Shoalhaven

Heads and it shows a very similar entrance condition to the photo taken a few months before.

Subsequently in the 1980s the entrance remained closed until it appears open again in the image of 18/07/1988 (Figure 4.7). This time the channel width exchanging estuarine-shoreface water was restricted to less than 150 m. The closing took about 2 years as identified in the 24/07/1990 Landsat 5 image. However, the next satellite passage on 09/08/1990 showed the entrance breached again (370 m wide). The following process of closing took approximately 3.5 years, as the mouth remained open until 24/01/1994. The subsequent Landsat image without cloud cover taken on 30/04/1994, showed the outlet completely closed.

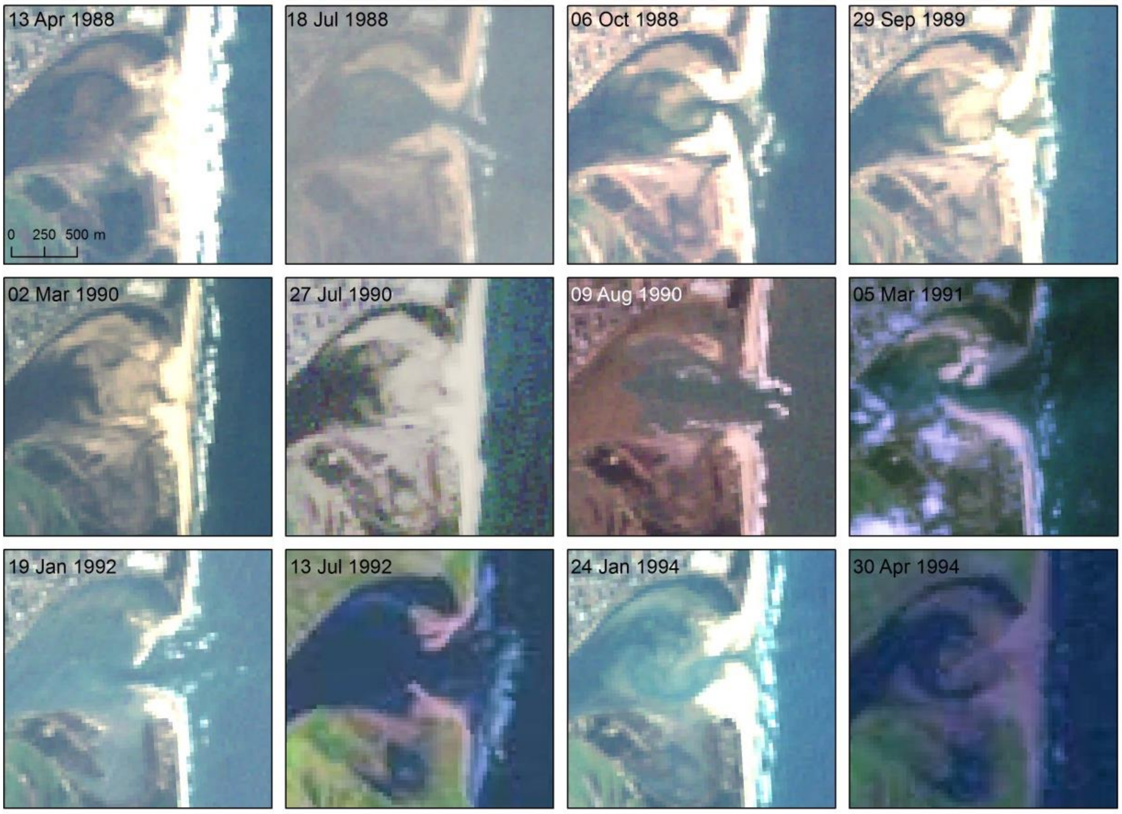


Figure 4.7 Landsat imagery compositions showing morphodynamic conditions of Shoalhaven Heads between 1988 and 1994. Note second breaching event months after the complete closing of the entrance in 1990. Satellite imagery © LP DAAC.

The mouth appeared open two more times between 30/04/1994 and 27/05/2013. The image of 16/09/1998 showed an approximately 150 m channel, whose width was halved in the 27/10/1998 image. The following images show a continual narrowing of the entrance until the complete closing observed in the 12/04/1999 image. Shoalhaven

Heads was opened again in the November/1999 images. The image of 06/11/1999 shows a narrow channel (approximately 70 m wide) separating Comerong Island from Seven Mile Beach, with the subsequent image of 22/11/1999 showing closing of the estuary and the one captured on 30/11/1999, showing that it was almost closed with only a small inlet. The following image of 02/02/2000 shows the estuary completely sealed with the beach reformed. These past two openings were conducted by the Council according to a report by Shoalhaven City Council (2006).

After that quick opening-closing event in late 1999, Shoalhaven Heads was captured open again only in the 30/06/2013 image (Figure 4.8), when the Shoalhaven City Council mechanically opened the estuary via the artificial low point/dry notch set at 2 m AHD (PWD, 1984), created to protect the Shoalhaven Heads village from flooding (Shoalhaven City Council, 2008). The gradual closing of the estuary started immediately after the breaching event and the following image taken on 16/07/2013 shows a much narrower channel connecting the estuary to the Tasman Sea. The image of 04/03/2014 is the last image where a small strip of water could still be seen, whereas the image captured on 29/03/2014 shows a completely sealed entrance.

The last time Shoalhaven Heads opened was in late August/2015. Once again Shoalhaven City Council mechanically bulldozed the entrance and the opening was captured in the 30/08/2015 image. Just over five months later, in the image of 02/03/2016, a small channel could still be observed, but on the following image of 18/03/2016, the beach berm was reformed and the entrance closed once again. The broad image retrospective presented in this study including more than 140 images capturing the morphology of Shoalhaven Heads adds important information to the understanding of sediment availability to the coast discussed by Wright (1970) and the morphodynamics of the river mouth. This retrospective has analysed breaching events, duration and qualitatively inferred the magnitude of these events based on channel width and entrance closing times enabling a better understanding of the sediment exchange between the estuary and the shoreface.

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channel width and entrance closing times enabling a better understanding of the sediment exchange between the estuary and the shoreface.

Although the overall image record comprises an average of 2 images per year during the 67-year period, there are some important time gaps which constrained the determination of mouth state during the 1950s, when no image was acquired, and the 1960's, when only one image was taken.

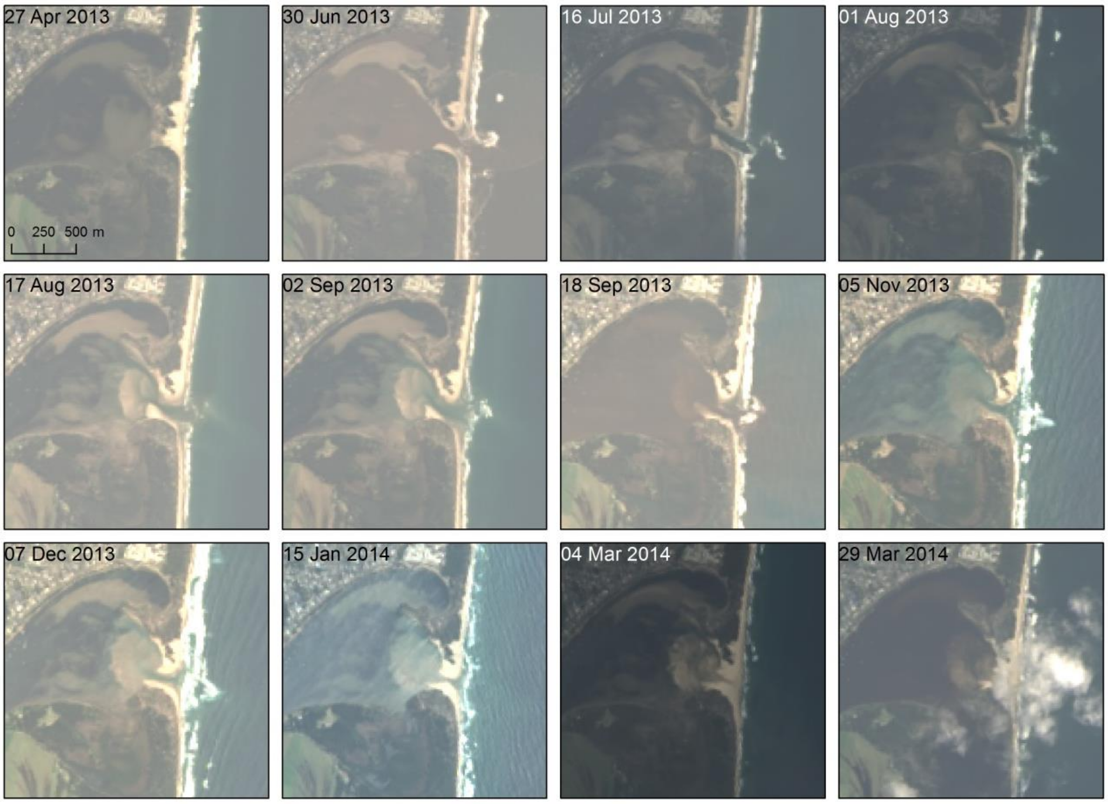

Figure 4.8 Landsat imagery compositions showing morphodynamic conditions of Shoalhaven Heads between 2013 and 2014. Satellite imagery © LP DAAC.

4.5 Bank erosion

Figure 4.9 shows the result of the bank erosion study in the estuary conducted for this thesis. Erosion can be observed in most of the reaches on both flanks of the estuary in the top map. Erosion was not identified in only 14 (7.2 %) out of 193 reaches. 13 (6.7 %) reaches had erosion for less than 25 % of the reach's extent, 8 (4.1 %) between 26 and 50 %, 19 (9.8 %) between 51 and 75 %, and 139 (72 %) reaches had erosion along the majority of the reach's extent. Reaches along which erosion was most extensive were spread throughout the estuary especially in the upper and lower parts. It seems that erosion presently experienced throughout the estuary is occurring in similar places to historical estuarine trends downstream from the Nowra Bridge observed by PWD (1988), as well as areas of evident erosion upstream from the bridge, mapped by Nolan (1997). An exception is a single reach composed of bedrock, located upstream from the Long Reach, where no erosion was observed in the present study.

Shallow and planar erosion were the two erosive mechanisms most commonly found as they occurred in 79 (40.1 %) and 57 (29.5 %) of the reaches, respectively. Mechanisms associated with rotational failure and failure of composition also occurred in the Shoalhaven estuary. Figure 4.10 shows some of the erosive mechanisms found in the estuary. Some areas mapped as shallow or planar, might actually represent depositional areas that have been subject to recent erosion.

Most of the reaches (105 of the 193 reaches) had no natural and/or artificial armouring, whereas, 88 (45.6 %) of the reaches had armouring along their extent. 67 (34.7 %) of the reaches had armouring along at least 25 % of their extent, and only 35 (18.1 %) of the reaches had armouring for more than 75 % of their extent.

Armouring types were identified as natural (bedrock) and engineered (revetment), with several reaches where both were present. 35 (18.1 %) reaches, mostly located upstream from Pig Island, were naturally armoured with bedrock only, whereas another 6 reaches had bedrock and either rock, concrete, or revetments of sandbags too. 40 (20.7 %) reaches, mostly around and downstream from Pig Island, were armoured with only rocks and another 4 reaches were armoured also with either concrete or wood. Three other reaches were armoured with tyres, wood or concrete. Figure 4.11 shows different types of armouring found in the estuary. When compared to the bank protection works maps in PWD (1988), most of the area downstream from Pig Island shows agreement, apart from a few rocky reaches on the left bank downstream from Numbaa Island, where no revetment was in place in the 1990’s. Erosion behind the revetment was also found in 34 (17.6 %) reaches. 26 of those 34 reaches where composed of rock revetment.

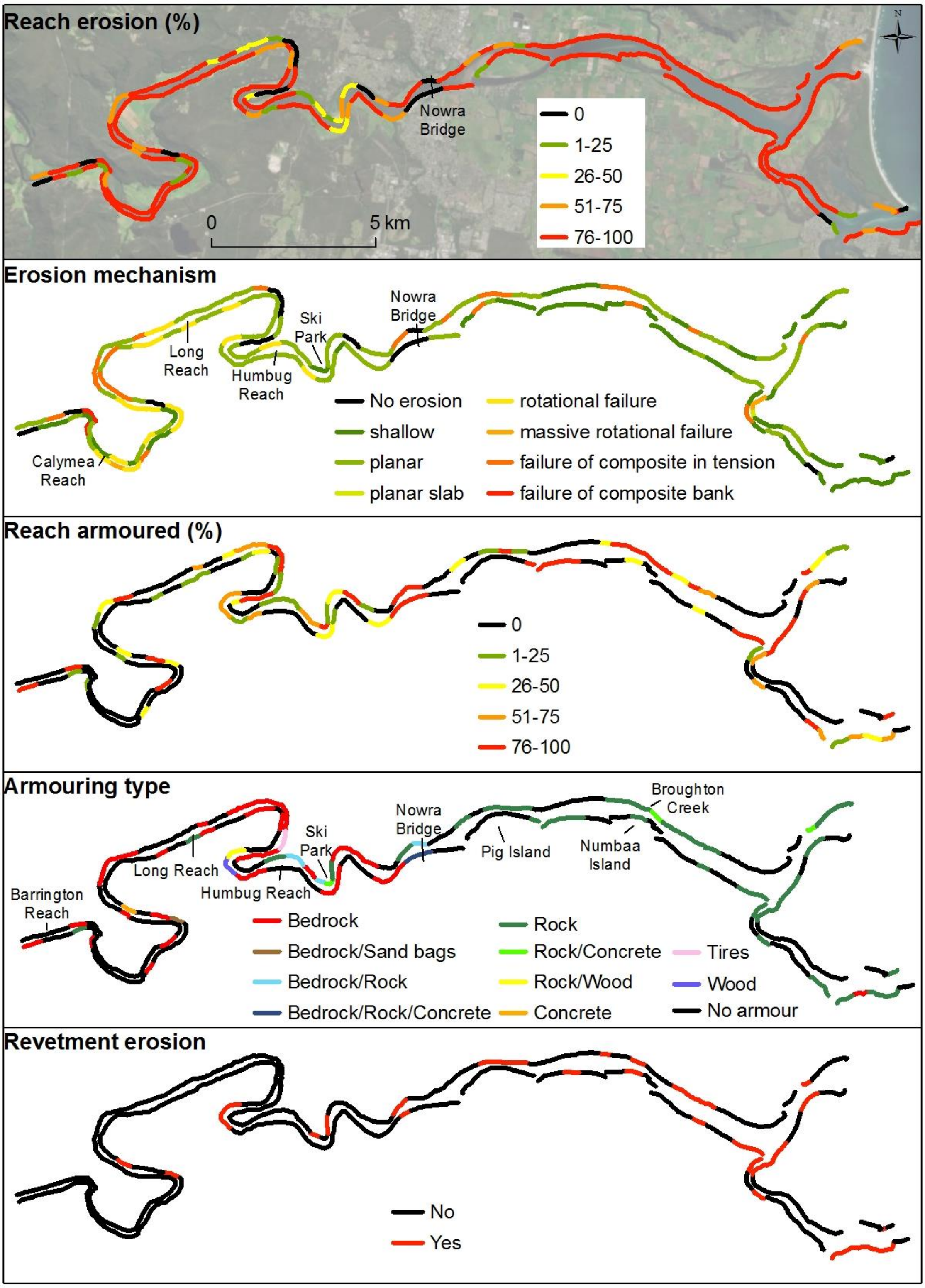

Figure 4.9 Bank erosion in the Shoalhaven estuary based on field observation datasheet surveys conducted in 2015. Maps from top to bottom indicate percent erosion in each of the 193 reaches (each of 500 m length); erosion mechanism; percentage of the reach that is armoured; type of natural and/or engineered bank armouring; and the existence of erosion behind the artificial armouring (revetment).

Figure 4.10 Erosion mechanisms in the Shoalhaven estuary. a) Shallow erosion on the left bank at the Shoalhaven Ski Park; b) Planar erosion on the left bank at the Humbug Reach; c) Rotational failure on the right bank upstream from Humbug Reach; d) Massive rotational failure on the right bank at Calymea Reach; e) Extensive rotational failure on the right bank of Long Reach; and f) Failure of composition in tension on the left bank upstream from Nowra Bridge. Photos by Mark Truskett.

Elevation comparison of LiDAR-derived DEM between 2001, 2004 and 2010 shows erosion and deposition of the estuarine banks (Figure 4.12). Due to the limited extent of the 2001 LiDAR coverage, the DEM difference between 2001 and 2004 could only be calculated for the section of the estuary downstream from Nowra Bridge to Numbaa Island. The difference in elevation in some areas may be just artefacts of the IDW interpolation technique and therefore, results must be interpreted with caution.

Between 2001 and 2004, erosion of up to 8 m wide by 2.1 m high occurred on the right bank (Figure 4.12a). Further downstream, 6 m long bank retreat by up to 2.6

m in height extended continuously for more than 50 m along the right bank and also on Numbaa Island (Figure 4.12b).

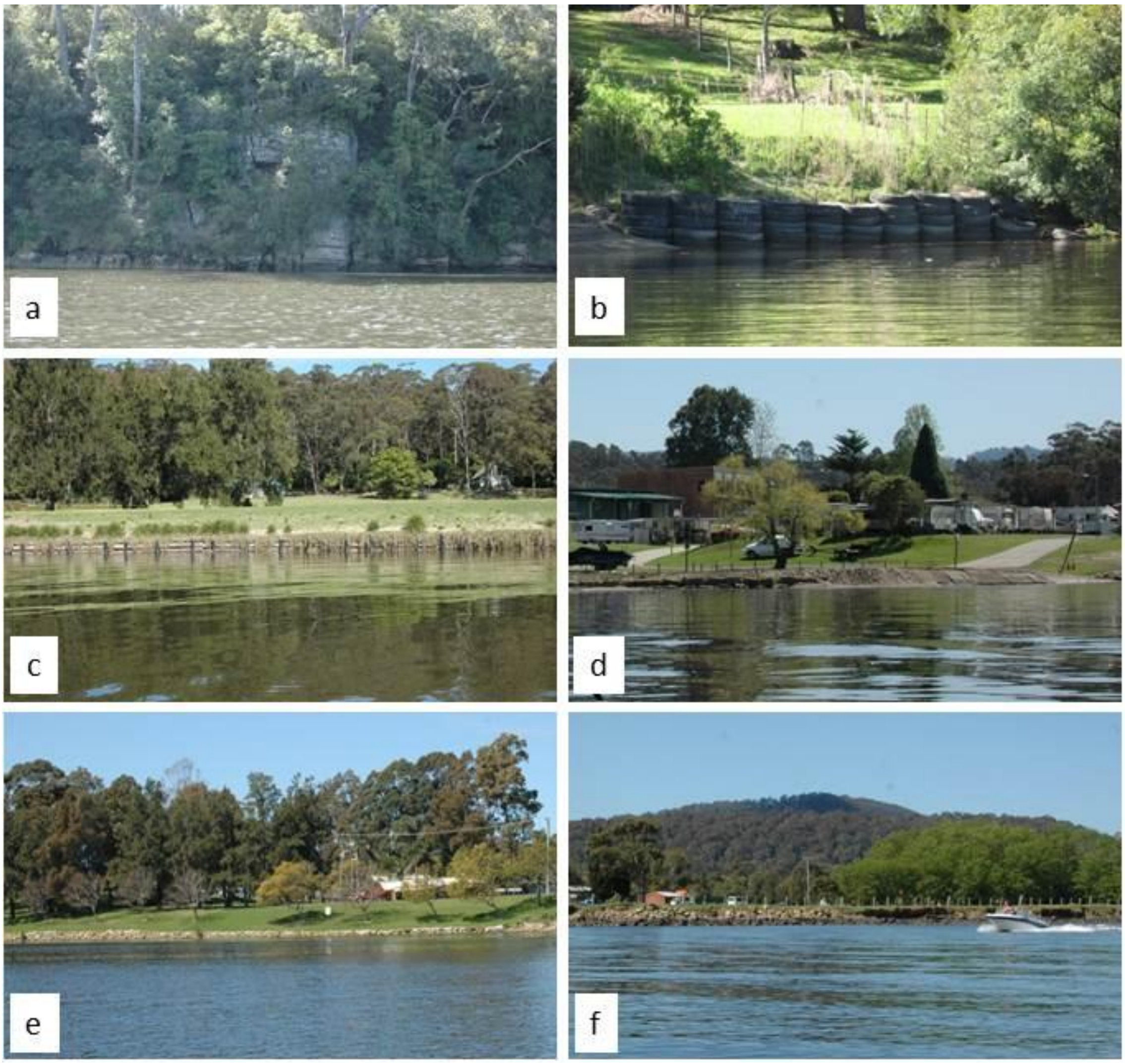

Figure 4.11 Armouring types in the Shoalhaven estuary. a) Bedrock on the left bank at the Barrington Reach; b) Tyres revetment on the left bank downstream from Long Reach; c) Wood revetment on the right bank near Humbug Reach; d) Concrete revetment on the left bank at the Shoalhaven Ski Park; e) Rock revetment on the right bank downstream from Nowra Bridge; and f) Failed rock revetment on the left bank downstream from the Broughton Creek confluence. Photos by Mark Truskett.

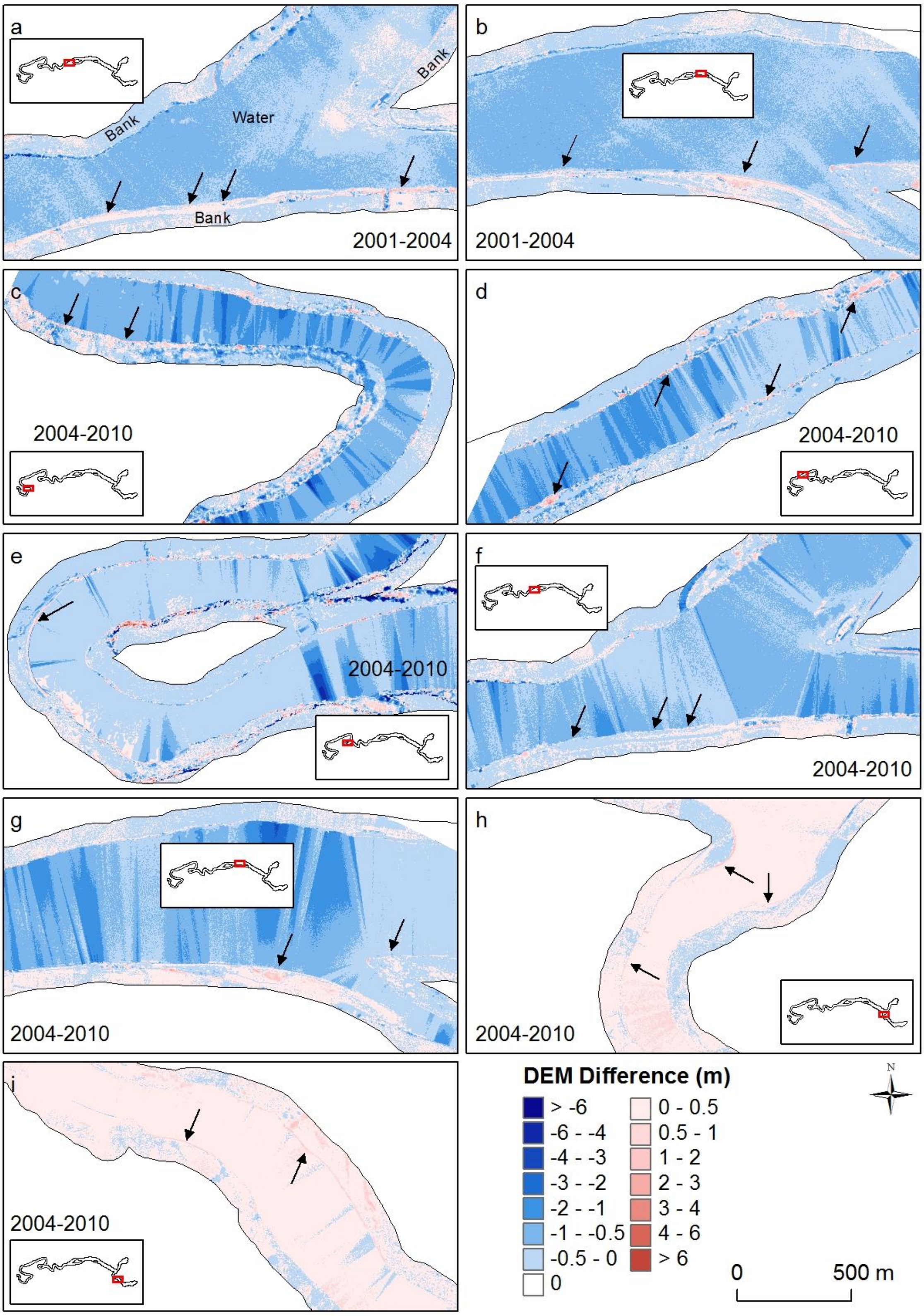

Figure 4.12 Elevation difference between DEMs based on 2001 and 2004 (a and b), and 2004 and 2010 (c-i) LiDAR data for the estuarine banks. Red areas mean erosion and blue areas mean accretion over time. The water body in between the 100 m wide banks must be ignored as differences are dominated by the disparity in water level between different surveys. Arrows indicate areas discussed in the text.

Between 2004 and 2010, a less linear type of erosion (up to 7 m wide and 4 m high) could be identified on the left bank upstream from Long Reach (Figure 4.12c), an area considered of severe erosion by Patterson Britton and Partners (2004), but of moderate to mild resistance by Glamore and Davey (2013). Erosion of areas of more than 4 m in height and 12 m in width ocurred on both banks in the middle of Long Reach (Figure 4.12d). An area of evident severe erosion (Nolan, 1997, Patterson Britton and Partners, 2004) with highly to moderately resistant bank on the left (Glamore and Davey, 2013), and minor erosive (Patterson Britton and Partners, 2004) with moderately to mildly resistant bank on the right hand side (Glamore and Davey, 2013).

The arrow at Figure 4.12e shows a 500 m long, 10 m wide, 2.5 m high linear stretch of erosion that took place probably before the wood revetment protection installation opposite to Long Point. This severe erosion spot (Patterson Britton and Partners, 2004) was classified by Glamore and Davey (2013) as highly resistant probably due to the artificial armouring in place.

Figure 4.12f shows that the erosion halted at most of the locations pointed out in Figure 4.12a, whereas Figure 4.12g shows that the erosion was still occurring on the right bank and to a lesser extent on Numbaa Island in between 2004 and 2010, when compared to the 2001-2004 period (Figure 4.12b).

The widening of Berrys Canal due to prominent loss of sediments from the banks between 2004 and 2010 is depicted on Figure 4.12h. Bank erosion (10 m wide by 2.2 m high) happened along 500 m of extent around O'Keefes Point, an area where considerable deposition occurred in between 1949 and 1984, according to a map published by PWD (1988), and to a lesser extent further downstream, a renowned erosive stretch of the canal that seems to have been eroding since 1901 (PWD, 1988) and that receeded at least 12 m between 1949 and 2002, according to data presented by Thompson (2012). Opposite to O'Keefes Point, on the Comerong Island side, a maximum of 4 m of bank recession, up to 1.4 m in elevation, was observed in one of the areas that changed the most (approximately 250 m of recession) since 1901 according to the PWD map (1988), an area renowned for erosion due to river flow, tidal scour and boat wash (Christian and Hill, 2002).

Significant erosion occurred downstream as well. Figure 4.12i shows that towards Crookhaven Heads, linear erosion happened continuously for 400 m, and up to

5 m width by 2 m in height, on the right bank at Apple Orchard Island, and also, for 750 m and up to 10 m width by 1.3 m in height for the left bank side (Nobles Island). This is a moderate erosion spot according to Patterson Britton and Partners (2004), that has receded more than 120 m since 1901 in accordance with results presented by PWD (1988) and Thompson (2012).

4.6 Estuarine sediments

Grain size analysis showed that the mean grain size ranged from very coarse sand to medium silt (-0.4 phi to 6 phi) (Figure 4.13). The general pattern is characterised by a decrease in grain size from coarse sand in the upper estuary to medium sand at both Shoalhaven and Crookhaven Heads. In the upper part of the estuary, very coarse sand occurs in shallow water, whereas finer fractions (medium to very fine sand) prevail in the pools. The most diverse textural part of the river is located between Pig Island and the 10 km upstream of Nowra Bridge. In this part, the river bank is composed of medium sand intercalated with finer sediments down to medium silt.

Downstream from Pig Island, medium sand prevails and the texture becomes finer near both entrances, with coarse silt just upstream of Shoalhaven Heads and fine sand adjacent to Orient Point. Towards both entrances the mean grain size increases again to medium sand due to the flood tide delta deposit at Crookhaven Heads and the penetration of marine sand transported by waves and wind at Shoalhaven Heads, an area of net upstream transport during low flow stages, as revealed by Wright et al. (1980).

Gravel fraction was found in 80 out of 123 samples within the estuary. Samples with gravel content above 2 % occured mostly upstream from Pig Island and in the Crookhaven entrance. Only one sample (E19) contained a gravel fraction above 20 %. Mud was found in all but 18 samples and these were mostly located in the lower estuary towards Crookhaven channel. As expected, mud content was higher in the deeper parts of the estuary and occurred mostly between Pig Island and Long Reach, where mud content of more than 90 % occurred in two individual samples. Mud content was also high in an area near Shoalhaven Heads where seven samples contained more than 20 % of mud and two samples more than 50 %. This muddy area is considered an environment of low hydrodynamic flow, partially isolated from the base flow when the estuary is not breached at Shoalhaven Heads.

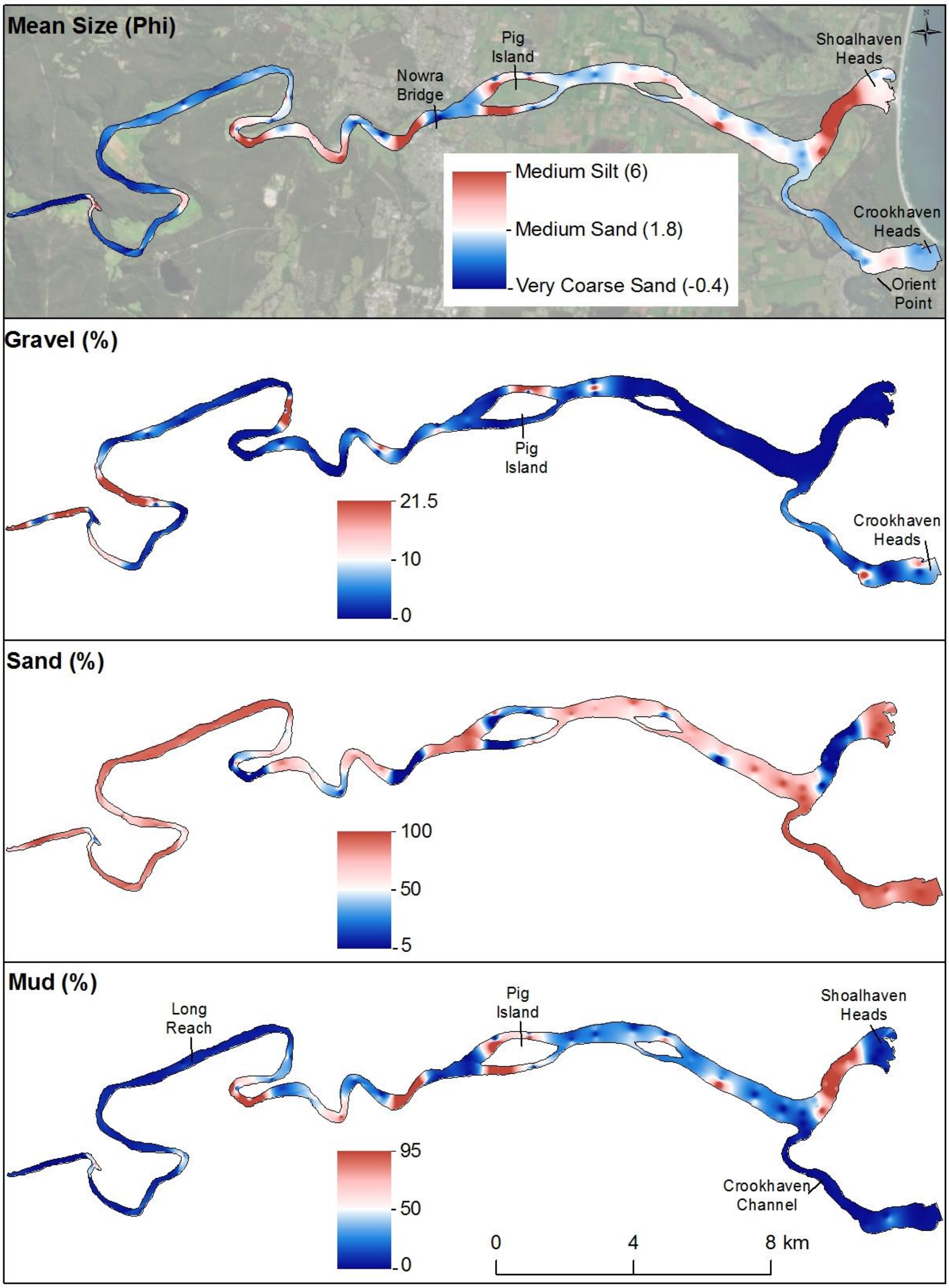

Figure 4.13 Mean grain size and percentage of gravel, sand and mud content in estuarine samples.

Sorting, skewness and kurtosis indicate how similar the samples are from a normal probability curve and are indicative of important sedimentary processes happening especially in the lower estuary. Environmental interpretation of these statistical parameters for most of the middle-upper estuary has proven to be difficult due to the existence of a complex general pattern of grain size, deep pools, meandering narrow channels, and mixing with material from eroding banks.

The dispersion around the average value, known as standard deviation or sorting varied from 0.6 phi to 2.8 phi (Figure 4.14). Sediments were moderately sorted in the upper estuary, mostly poorly sorted upstream of Comerong Island, and moderately sorted to moderately well sorted around both entrances. The very poorly sorted mud sediments just before Shoalhaven Heads can be explained by the restricted hydrodynamic conditions experienced in this area after the gradual closing of the entrance during the months prior to the sampling.

The skewness or asymmetry is determined by the relative importance of the tails of the distribution. The skewness has a positive or negative value when more fine or coarse material is present than in a normal distribution. Sediments in the estuary varied from coarse skewed (-0.24) to very fine skewed (0.55), with most of the samples considered fine skewed. Sediments with symmetrical distribution were observed at Long Reach, around Pig Island, between Berrys Canal and Crookhaven Heads, and in two of the four samples collected at Shoalhaven Heads. The moderately sorted symmetrical samples that predominate along the Crookhaven channel and to a lesser extent near Shoalhaven Heads entrance indicate that marine-derived sands are penetrating the estuary.

Very fine skewed samples were found scattered downstream from Long Reach towards Shoalhaven Heads and also in a sample near Crookhaven Heads. The fact that there are patches of very fine skewed poorly sorted mud sediments just upstream of Shoalhaven Heads, indicates a mix of fluvial and marine material, as strongly skewed samples are generally obtained from zones of environmental mixing (Folk, 1966). Coarse skewed sediments also occurred between Berrys Canal and Crookhaven Heads.

Kurtosis measures the peakedness of the distribution. If a distribution is flatter than a normal one, it is called Platykurtic; if more peaked, it is called Leptokurtic. Kurtosis in the estuarine sediments varied from Platykurtic (0.73) to very Leptokurtic (2.8). 49 out of 123 samples were normal (Mesokurtic) and found all over the estuary, including near both entrances at Shoalhaven Heads and Crookhaven Heads, and also in the upper and middle estuary, where patches of Mesokurtic surficial sediments alternate with Leptokurtic ones.

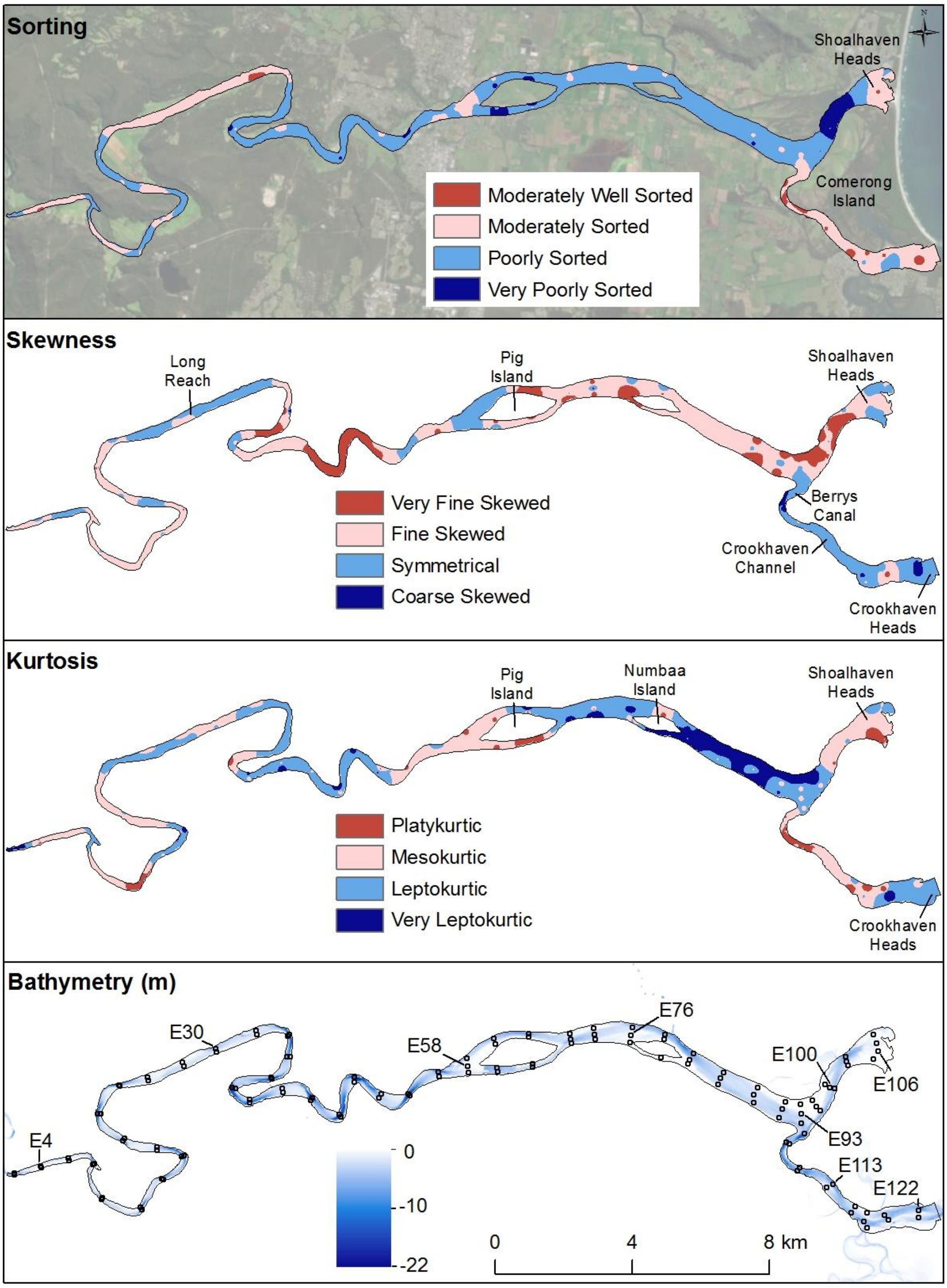

Figure 4.14 Sorting, skewness, kurtosis and location of the estuarine samples. Labels identify samples selected for further sediment analyses. Bathymetric data © NSW Government. Office of Environment and Heritage (OEH) 2006.

Sediments with very peaked distribution curves (Very Leptokurtic) occur especially downstream of Numbaa Island. The occurrence of very Leptokurtic material implies a mix of two different materials (fluvial and marine), suggesting that part of the (marine) sediment achieved its sorting elsewhere in a high-energy environment, and was transported with its size characteristics unmodified into another environment (estuarine), as discussed by Folk and Ward (1957).

This extensive surficial sediment sampling effort is the first of its kind known in the Shoalhaven estuary. Before this study, only scattered samples were collected, making it difficult to draw comparisons with previous findings. Nevertheless, a small section in the middle estuary was studied by Boyd et al. (1977). These authors collected 11 estuarine samples centered at Pig Island in 1976, and therefore, a comparison of the results can be made.

Figure 4.15 depicts the interpolation of mean grain size values around Pig Island from Boyd et al. (1977). It clearly shows a very different distribution than the one presented in this thesis. The 11 samples collected varied from 0.67 phi to 2.64 phi, with coarser sediments located both on the south channel and upstream from Pig Island. The top map at Figure 4.13 shows a much more diverse surficial distribution in the same area. Going downstream, sediments are much finer, then transition into coarser sand similar to 1976 values just upstream from Pig Island. In the south channel very fine sand (3.89 phi) and very coarse silt (4.62 phi) occurs, whereas downstream of Pig Island, sediments were coarser (0.94 phi - 2.06 phi).

It is difficult to determine the reasons for the differences between the surficial sediment values presented by Boyd et al. (1977) and the ones in this thesis. Whereas modifications in the hydraulic regimes may be a cause of the disparity, influencing not only the velocities and water surface elevation, but also the estuarine turbidity maxima, sampling methodology was different and channel erosion in the last 40 years might have contributed to the changes. The southern channel has been subject to extensive dredging for sand extraction (Figure 4.3) and the finer sediments there can be considered residual of the extraction of coarser material

Figure 4.16 shows selected examples of scanning electron microscope (SEM) images of individual quartz grains present in estuarine sediment samples, indicating a qualitative degree of roundness, sphericity and chemical weathering. Images of all 16 quartz grains analysed per estuarine sample are found in Appendix 5.

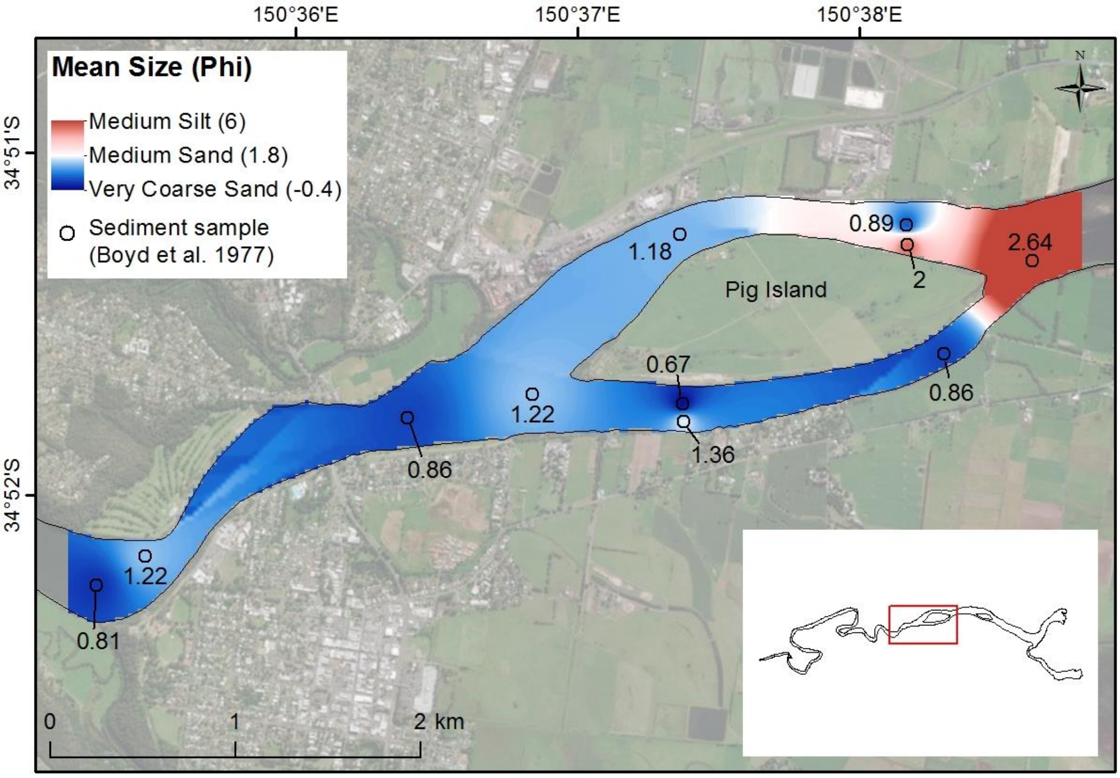

Figure 4.15 Mean grain size distribution after Boyd et al. (1977). Sample values converted from mm to phi scale and labelled in the map. Phi values were interpolated at 25 m pixels and displayed using the same symbology used to create the top map in Figure 4.14.

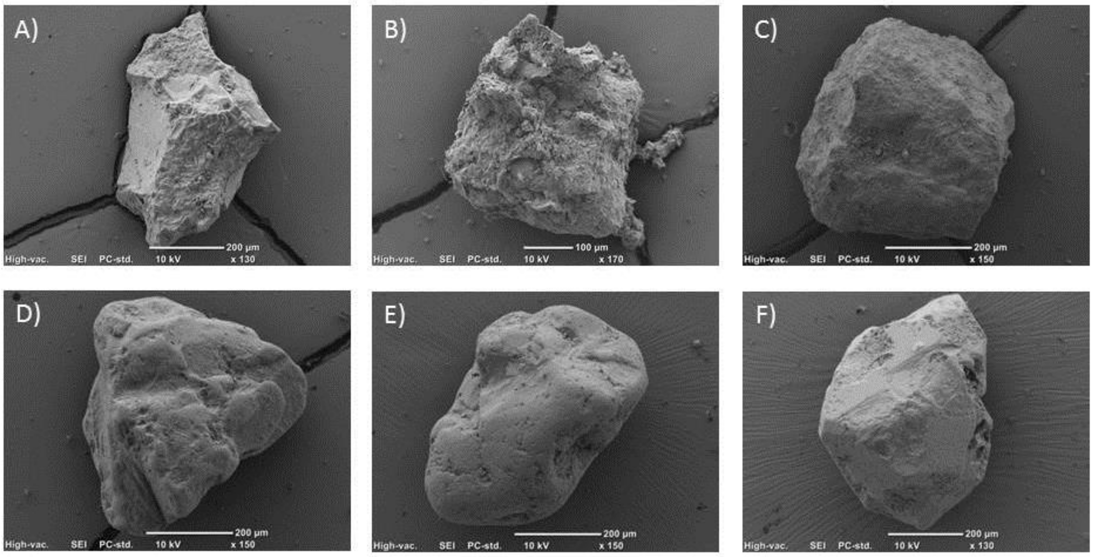

Figure 4.16 Selected examples of SEM images of quartz grains in the 1-2 phi fraction in estuarine samples. A) Sample E58 located upstream of Pig Island; B) Sample E76 located upstream of Numbaa Island; C) Sample E93 located in front of Old Man Island; D) Sample E106 located at Shoalhaven Heads; E) Sample E113 located at the Crookhaven channel; and F) Sample E122 located at Crookhaven Heads. Images of all 16 quartz grains analysed per estuarine sample are found in Appendix 5.

Roundness and sphericity are two properties that have significance for the study of the effect of the transport process on the sediments, revealing the modification of grains by abrasion and solution (Pettijohn et al., 1987), as well as winnowing by currents. Roundness refers to the degree of sharpness of the corners and edges of a particle grain, and reflects the abrasion history in particular. Sphericity has hydraulic importance and determines how easy a grain is entrained and how fast it settles. Sphericity measures the departure of a body from equidimensionality, or in plain English, how close to a perfect sphere a grain is. A particle has high sphericity, if all three axes have about the same length. If the axes differ markedly in length, the particle has low sphericity. Chemical weathering is the result of chemical reaction between minerals and air or water. In quartz grains, it results in various types of etching and overgrowth features, such as solution pits and crevasses, silica globules, flowers and pellicles, crystalline overgrowth and trapped diatoms (Madhavaraju et al., 2009).

The roundness of quartz grains in the 1-2 phi fraction found in the middle of the channel (Figure 4.14), just upstream from Pig Island (E58) varied from very angular to rounded and some grains tended to have low sphericity, whereas chemical weathering could be observed on most grains (Figure 4.16a). Immediately upstream from Numbaa Island (E76), sediments were angular to rounded, sphericity increased and strong chemical weathering was observed in all 16 grains (Figure 4.16b). Further downstream, in front of Old Man Island (E93), quartz grains were also angular to rounded (Figure 4.16c), but angularity decreased in most of the grains and weathering attack by chemical processes was not as strong as in sample E76. The sample collected at Shoalhaven Heads (E106) was mostly composed of sub-angular grains with varying degrees of chemical weathering (from none to strong) and sphericity (from high to low) (Figure 4.16d). Towards Crookhaven Heads (E113), estuarine grains were sub-angular to rounded, sphericity increased and no strong chemical weathering was observed on any grain. Moreover, some grains showed very little evidence of chemical weathering marks (Figure 4.16e). Sample E122, located at Crookhaven Heads, was composed of sub-angular to sub-rounded grains, evidence for chemical weathering was considered weak and absent in some grains (Figure 4.16f).

In general terms, the SEM images show an unexpected similarity in the quartz grains among the estuarine samples, although roundness and sphericity increases and chemical weathering decreases from Pig Island towards both entrances. During sampling design, it was expected to find more contrast between samples near the entrances and the ones further upstream, reflecting grains that were subjected to marine and fluvial environments, respectively. This weak contrast can possibly be explained by the fact that the sampling effort occurred five months after a major flood event that delivered lots of fluvial sediments to the shore and therefore, the lower end of the estuary, especially Shoalhaven and Crookhaven channels had a mixed population of fluvial and marine grains.

4.7 Mineralogy

Sediment contributions to the estuary were characterised via mineral composition using X-ray diffraction (XRD). Quartz (68.7-92.6 %) and feldspars (5.3-14.7 %) are the most abundant minerals found in the sediment samples collected from the estuary (Table 4.1). Their high abundance was expected, because these two minerals are so ubiquitous in metamorphic and igneous rocks. The feldspar concentration varied from 5.3 % to 14.7 %, which is similar to the unweighted average of 10.7 % found in sediments of the world's biggest rivers by Potter (1978). In the Shoalhaven River a decreasing trend was observed further downstream in the estuary. Albite and orthoclase were the most common forms of feldspars with concentrations of up to 5.3 % and 6.1 % found in sample E4. Labradorite was present in all samples and reached its highest concentration in sample E58, whereas microcline's concentration reached 3 % in sample E100, but was absent in sample E106.

The presence of albite and labradorite in estuarine samples can be derived from sandstones and siltstones of the Berry Formation that occur in the lower Shoalhaven Catchment. Average composition of sediments from Berry Formation shows 7 % of plagioclase feldspars (Bowman, 1974). Some minor alkali feldspars were also present (up to 5 %) in the samples analysed by Bowman (1974) indicating a possible origin for orthoclase and microcline found in the estuary, although orthoclase and microcline, the feldspar formed during slow cooling of orthoclase, are common minerals in granites of the Lachlan Fold Belt.

Carbonates were absent, apart from 0.1 % of calcite and 0.4 % of aragonite found in sample E100 and 0.2 % of Mg calcite found in sample E106. Clay minerals were present in the estuarine samples in the form of muscovite, illite and kaolinite.

Clay mineral content varied from 2 % near Shoalhaven Heads (E106) and Crookhaven Heads (E122) to 18.1 % along the Shoalhaven channel (E100), and showed the existence of two different surficial sediment types: the clay mineral-depleted sediments near Shoalhaven Heads (E106) and along the Crookhaven channel (E113 and E122), and the clay mineral-rich sediments upstream of Old Man Island (E4, E30, E58, E76, E93 and E100). Muscovite was absent in samples E106, E113 and E122 and very low at E4, but its concentrations were the highest among the other clay minerals in the other samples, reaching 10.2 % of the total weight in the very coarse silt sample E100 composed of 60 % of mud fraction, and 5.1 % in sample E58. Illite and kaolinite were found in all samples and their maximum concentration was 4.6 % and 3 %, respectively, in sample E100.

Table 4.1 Mineralogy of estuarine surficial sediments (wt. %) of size fraction finer than 0 phi. Feldspars include orthoclase, albide, labradorite and microcline.

Sample	Chi square	Quartz	Felds pars	Calcite	Mg Calcite	Arago nite	Musco vite	Illite	Kaoli nite
E4	2.67	82.3	14	0	0	0	0.4	2.1	1.2
E30	2.88	82	12.1	0	0	0	2.6	1.7	1.7
E58	2.36	82.1	7.7	0	0	0	5.1	3.2	1.9
E76	3.28	79.4	14.7	0	0	0	3.3	1.6	1.1
E93	2.59	82.6	9.7	0	0	0	3.8	2.7	1.3
E100	2.57	68.7	13.1	0.1	0	0.4	10.2	4.6	3
E106	3.23	89.8	8.1	0	0.2	0	0	1.5	0.5
E113	3.21	89.7	8.1	0	0	0	0	1.4	0.8
E122	2.66	92.6	5.3	0	0	0	0	1.6	0.4

The presence of muscovite is not surprising as this elongated mineral was present in all rock samples from the Megalong Conglomerate and Berry Formation groups analysed by Harwood (1999) near Marulan (Figure 3.1) and also around clasts in samples from Berry Formation analysed by Bowman (1974). The latter also found an average composition of 46 % of clay minerals, cement and matrix obtained in the same sediments. XRD examination of some of these samples by Bowman (1974) showed that the average clay composition is 65 % of illite and 10 % of kaolinite. All three clay minerals were also observed in samples of the Ordovician sequence in the Shoalhaven catchment analysed by Jones et al. (1993), indicating a probable catchment origin of these clay minerals in the estuary.

The mineralogical analysis points to different sources of sediments found in the estuary. In general terms, samples E106, E113 and E122, located at Shoalhaven Heads, Crookhaven channel and Crookhaven Heads, respectively, have lower concentrations of feldspars and clay minerals than the remaining estuarine samples located further upstream, suggesting marine sand penetration in the lower estuary.

4.8 Sidescan sonar

Bedforms are features of the relief developed on a bed of a fluid flow (Allen, 1968) and have been identified in estuaries with the aid of sidescan sonar by Harris and Collins (1984), Nichols et al. (1991), Cuadrado et al. (2003), Wu et al. (2009), Wewetzer (1999), among others.

In the Shoalhaven estuary, different bedforms were observed in different parts of the estuary, reflecting the dynamic interaction between the properties of the flow and the grains that participate in the movement of the sediment load. The complex depositional environment of the Shoalhaven estuary and the associated near-surface geometries of the lithofacies are directly related to the maturity or degree of infilling experienced in this estuary as pointed out by Roy et al. (1980).

Bedforms could be identified throughout much of the Shoalhaven estuary (Figure 4.17). These were concentrated around Long Reach and downstream from Pig Island, and were scarce and scattered in a 9 km reach upstream from Pig Island.

In the upper part of the estuary (Figure 4.17a), most bedforms occur at 3 m of depth below AHD or shallower, and are associated with poorly sorted to moderately sorted coarse sands (0-1 phi). Bedforms were mostly asymmetrical largescale ripples forming terraces with average spacing of approximately 20 m, transverse to the main component of flow. Their upstream slopes are gentle and downstream slopes steep. Some of the largescale ripples have straight crests that extend for up to 140 m. Some smaller ripples (approximately 3 m in length) also occur in the area associated or not with larger ones. In the southwestern area of Figure 4.17, largescale ripples occur in different directions indicating that these bedforms have been formed by different flow directions.

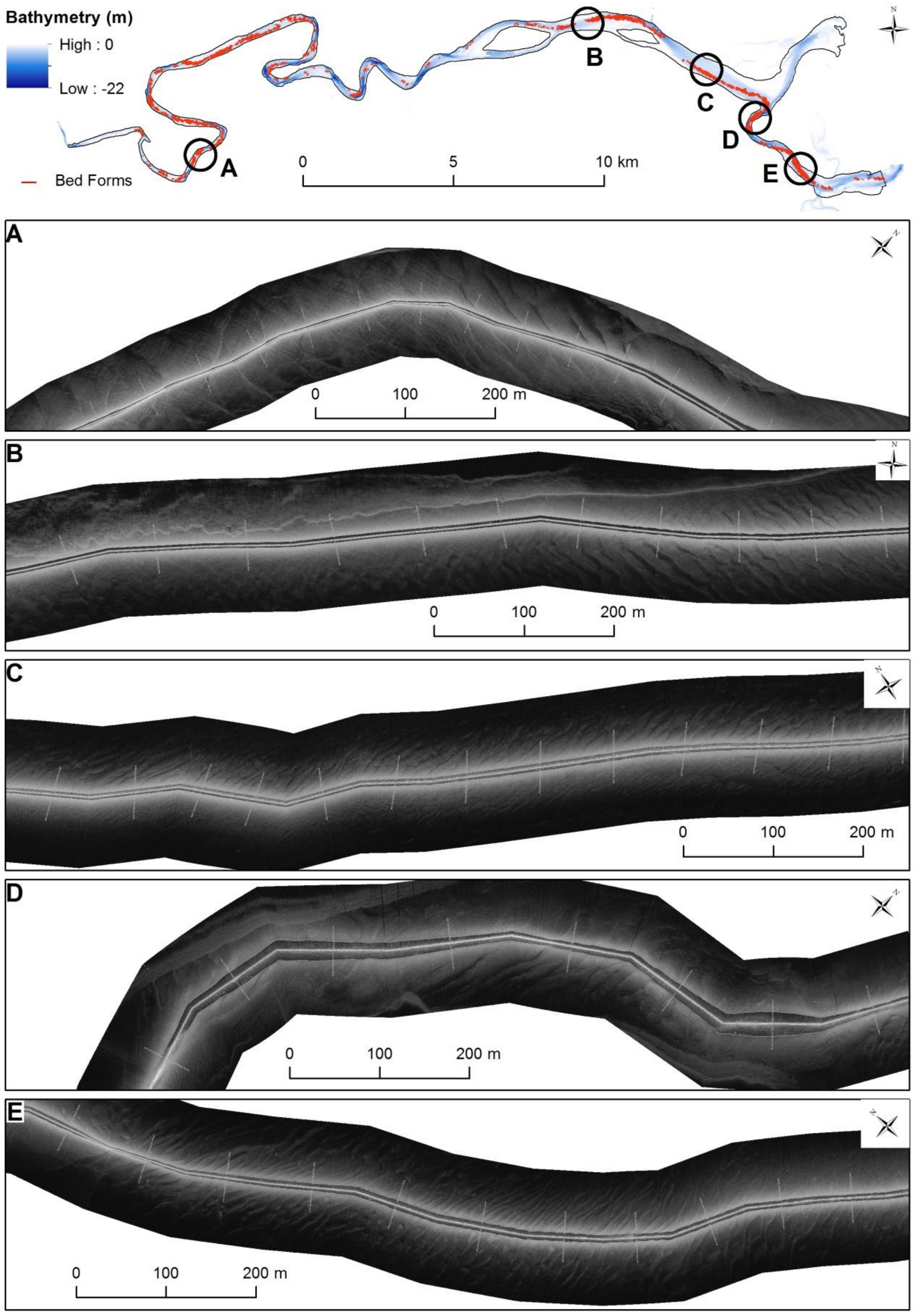

Figure 4.17 Sonographs showing bedforms such as asymmetrical largescale ripples at five different locations (a-e) along the Shoalhaven estuary. Bathymetric data © NSW Government. Office of Environment and Heritage (OEH) 2006.

The bedforms in the estuarine area that extends for 9 km immediately upstream from Pig Island is composed of small hummocky features, representing bidirectional cross bedding, and judging from the orientation of the lee side of the asymmetrical largescale ripples present in Figure 4.17a and b, this area represents a portion of the estuary where both tide and fresh water input exert their influence but none dominate.

Figure 4.17b shows the sonograph of the estuarine bottom downstream from Pig Island, where largescale asymmetrical ripple marks occurs. These 10-m spaced ripples were up to 8 m in length. Their sinuous crests extend for up to 120 m. These ripples also seem to be moving upstream as their downstream slopes are gentle and upstream slopes are steep. They occur in 2-3 m water depth and are composed of poorly sorted medium sand (approximately 1.5 phi). To the northwest of those ripple marks, a seagrass meadow can be seen in the sonograph.

Figure 4.17c shows the sonographs between Numbaa Island and the bifurcation of Berrys Canal, where asymmetrical largescale ripples were 8-10 m in length and seemed to be significantly flatter than the ones immediately downstream from Pig Island. They are located in 2.5-3.5 m depth and are composed of poorly sorted medium to very fine sand (1.8-3.3 phi).

Further downstream, at Berrys Canal (Figure 4.17d), asymmetrical largescale ripples of varied lengths were observed down to 10 m depth. These ripples were composed of moderately sorted medium (1.5 phi) sand and were moving upstream. The largest ripples were up to 20 m in length and had crests that extend for up to 180 m. Smaller ripples of 2 m in length were also observed in deeper areas.

Figure 4.17e also shows another area where largescale ripples occur. These ripples were 6-12 m in length and had straight crests of up to 170 m. They were located in 3-6.5 m depth, composed of moderately sorted medium sand (approximately 1.2 phi), and also seem to be moving upstream as their downstream slopes are gentle and upstream slopes are steep indicating reshaping in response to flood tide currents. Some of these largescale ripples can be seen even in the aerial photograph taken on December/2013 and shown in Figure 4.18.

Although it has been demonstrated that largescale ripple asymmetries may reverse between ebb and flood flows (Harris, 1982), and therefore are tide dependent, the results presented of largescale ripples moving downstream in the upper estuary and upstream in the lower estuary seems to be in accordance with the dominant processes of sediment movement expected in most wave-influenced estuaries of eastern Australia.

Figure 4.18 Largescale asymmetrical ripples in the Crookhaven channel can be seen in the December/2013 aerial photograph. Imagery © NSW Government. Land and Property Information (LPI) 2013.

The existence of flood-tidal deltas on the Crookhaven channel is a testimony of the asymmetry in the magnitude and duration of tidal flows, resulting in a flood oriented net sediment transport moving marine sediments up the estuary, and therefore a sink for the coastal budget. Flood dominance occurs when currents in the flood direction are stronger but have a shorter duration than ebb currents (Fry and Aubrey, 1990), implying that the lateral erosion and scouring of Berrys Canal and the Crookhaven channel as a whole, tends to transport sediments up the estuary under moderate flow conditions.

The bedforms described in Figure 4.17e, at the Crookhaven channel, under low flow stage conditions, are characteristic of wave action superimposed on bidirectional tidal flows, that enhances flood-tide currents and produces extensive flood-tidal deltas landward of the entrance as pointed out by Roy et al. (1980) and shown in Figure 4.19. During storms events a portion of these sediments are transported to the nearshore. Despite the morphologic modifications in the flood-tidal delta in the Crookhaven throughout the years, it appears that the deposits are hydraulically stable as not much change can be observed even after the flood events of 2013 and 2015 (Figure 4.19).

Figure 4.19 Flood tidal deposit composed of marine sand in the Crookhaven channel from September/2005 to January/2016. Minimum changes in the deposit are observed even after the recent flood events. Google Earth images © 2016 DigitalGlobe and CNES/Astrium.

4.9 Summary

Two main estuaries connect the Shoalhaven River and the Coonemia Creek to the northernmost and southernmost tertiary level compartments, respectively. The confined fluvial channel of the Shoalhaven barrier estuary reaches a maximum depth of approximately 21 m, but more than 80 % of the relative area is found in much shallower waters of less than 3 m, restricting the total accommodation space to only 55.4 x 10^6 m^3. The mature stage of evolution and the confined accommodation space facilitates estuarine bank erosion and restricts the deposition of fluvial sediments in the estuary. Lake Wollumboola, the saline coastal lagoon that connects Coonemia Creek to Warrain Beach, is very shallow (maximum depths of 1.1 m) and has a total accommodation space of approximately 1.9 x 10^6 m^3.

Erosion occurs in most of the Shoalhaven estuarine banks of the main channel, mostly in the form of shallow or planar mechanism, with extensive rotation failure happening in some banks and considerable volumes of material being eroded on both sides of the estuary. Less than 20 % of the analysed reaches had parts of the banks naturally armoured with bedrock, whereas 25 % had some sort of revetment in parts of their extension, with varying degrees of protection success.

In the past 34 years, the Shoalhaven estuary acted as a sink for the budget, receiving sediments from the catchment and also marine-derived sand via both Shoalhaven Heads and Crookhaven Heads, as indicated by volume accretion over the years, the texture and mineralogy of in-channel sediments, and the flood-tidal deltas on the Crookhaven channel. The estuary experienced an estimated net accretion of approximately 1,020,000 m^3 of sediment between 1981 and 2006, despite the gross volume loss observed in the lower end of the estuary, especially the erosion dominated processes in most of the Crookhaven channel that has become deeper and wider.

The surficial sediments of the Shoalhaven estuary are composed of a complex general pattern characterised by a decrease in granulometry from coarse sand in the upper estuary to medium sand on both Shoalhaven and Crookhaven Heads, and muddy areas where mean grain size reached 6 phi. Differences in texture and mineralogy of the sediments, and to a lesser degree, the characteristics of quartz grains, permitted the identification of two distinguishable groups of sand, one of marine origin in the Crookhaven channel and also at Shoalhaven Heads, and the other one derived from the river itself, occupying most of the estuary.

Fluvial and estuarine sediment discharge to the nearshore occurs mostly during flood events when Shoalhaven Heads is open. The berm at Shoalhaven Heads was breached in 1961, 1974-1980, 1988-1994, two times in 1998-1999 and twice more through the course of this study, in 2013-2014 and 2015-2016. The last four times the opening occurred mechanically and lasted between four and nine months only. Despite the artificially breaching by the Shoalhaven City Council during flood events, the channel that leads to Shoalhaven Heads is infilling as demonstrated by the deposition of sediments that occurred between 1981 and 2006.

Chapter 5: Beach-barrier systems

This chapter contains the results and discussion of the data analyses for the beach-barrier systems in the Shoalhaven coastal compartment. A short introduction to the topic is provided first. Subsequent sections contain information about the texture, shape and mineralogy of the beach sediments, the morphology of the beach-barrier systems, beach behaviour at decadal and short time scales, and Shoalhaven Heads dynamics during breaching events. These sections were designed to investigate the peculiarities of beach sediments and the possibility of exchange between the three tertiary level compartments, and characterise the behaviour of the three beach-barrier systems in order to estimate the beach volumetric change that occurred to the three tertiary level compartments over time. Then, a final section summarises the findings in terms of sediment transport and processes for the coastal budget.

5.1 Introduction

The Shoalhaven compartment is situated in an embayed coast comprising sandy beaches flanked by rocky cliffed Permian headlands in the southern part of the Sydney Basin. The hilly northern headland of Gerroa is composed of rocks of the basal Westley Park Sandstone Member, one of the eight subdivisions of the Broughton Formation (Carr, 1984). The Westley Park Sandstone is composed of massive to flat cross-bedded, poorly-sorted green-grey fine volcarenites containing numerous clasts of latite and minor siltstones and conglomerates (Johnson, 1974, Carr, 1984). The sandstone cliffs of Beecroft Peninsula are characterised by large eroded joints composed of well- to moderately-sorted, fine to coarse grained, yellow-brown to off-white quartzose arenite to sublitharenite rocks of the Snapper Point Formation containing both moderate and low-angle cross beds (Johnson, 1974). Between these two headlands, mid to dark grey diamictite of the Wandrawandian Siltstones forms Crookhaven Heads and Penguin Head.

Three wave-dominated Quaternary deposits form the beach and barrier systems of the Shoalhaven. The main deposit is the northern one, as the Shoalhaven River has contributed sand to the coast for the past few millennia, and this has enabled the development of a prograded barrier with a sequence of ‘relict’ foredune ridges along

Seven Mile Beach (Wright, 1970, Short and Woodroffe, 2009). The chronology of sand-barrier progradation along Seven Mile Beach has been investigated by Thom et al. (1978), using radiocarbon dating of shells recovered from depths of 1 to 16 m below mean sea-level. These authors demonstrated a decelerating progradation over the past 7,500 years.

The beach-ridge development and beach sediments at Seven Mile Beach-Comerong Island were first examined by Wright (1970), whose investigations aimed to elucidate the depositional history and processes of the formation of the barrier system. He concluded that the topographic and sedimentological character of the sand deposits flanking the mouth of the Shoalhaven River are related to two major control variables: the wave regime and proximity to the mouth of the river. The river efflux was the principal source of sand to the relict ridges and the modern beach that constitutes a continuous and uninterrupted depositional sequence prograded seaward since the postglacial sea-level transgression. Several aspects of the morphology of the mouth of the Shoalhaven River led him to conclude that after a breaching event, sediments accumulate in the form of a crescentic river-mouth bar seawards of the outlet and as broad subaqueous levees capped by swash bars, and post-depositional shoreward return of sands by shoaling waves produces a constricted outlet (Wright, 1977).

The second beach-barrier system at Culburra, south of Shoalhaven River, has been examined by PWD (1980) and interpreted as a receded barrier due to the existence of a narrow barrier with a single foredune ridge. The barrier sand unit appears to have over-ridden the back barrier sand unit and possibly an estuarine mud unit. By the time of the writing of this thesis, no previous work regarding barrier formation was identified for the third and southernmost Warrain-Currarong embayment.

Morphodynamic changes on the beach, the active part of the barriers, have been described by Wright (1967) and Wright and Short (1983) for the Seven Mile Beach-Comerong Island, and by PWD (1980) for Culburra Beach tertiary level compartments. Apart from these individual beach studies, Johnson (1974) conducted beach profiles and sediment investigations at the three embayments twice over the course of a year, as part of his thesis. Despite these sporadic observations, there has not been enough monitoring of the northern, middle and south parts of the embayments continuously during a sufficiently long period to measure the dynamic seasonal or longer-term changes associated with the beach.

The long Seven Mile Beach-Comerong Island Beach sweeps in a gentle arc, facing southeast at Gerroa, east at Shoalhaven Heads and then, northeast at the south of Comerong Island (Figure 5.1). The northern end is a wide flat beach with waves spilling over a wide shallow attached bar cut by rip currents every 300 m (low tide terrace - LTT/ transverse bar & rip - TBR). At Shoalhaven Heads (transverse bar & rip - TBR/ long bar through - LBT) and Comerong Island (transverse bar & rip - TBR/ rhythmic bar & beach - RBB), a double bar system operates along most of the beach with an attached bar cut by periodic rips (Short, 2007).

Further south, at Culburra, the east-facing beach in the north and middle (transverse bar & rip - TBR) has a single bar, that is usually cut by rips every 200-300 m. The north-facing beach at the southern part of Culburra (low tide terrace - LTT) has lower waves and therefore, fewer rip currents. The Warrain-Currarong embayment is an east-facing beach in the north (Warrain), with less wave energy at the southern end (Warrain) which faces northeast. The beach has an attached bar usually at Warrain (low tide terrace - LTT/ transverse bar & rip - TBR) with 200-300 m spacing of rips also in the middle (transverse bar & rip - TBR), with rips decreasing in occurrence and strength along Currarong Beach (low tide terrace - LTT) (Short, 2007).

5.2 Beach sediments

The three beaches showed marked longshore variation in granulometry (Figure 5.1). Grain size analysis showed that the mean grain size ranged from coarse to fine sand size (1 phi to 2.4 phi). The coarsest sample (1 phi) was found near Lake Wollumboola at Warrain (B11) and the finest (2.4 phi) near Currarong (B2). Beach granulometry gets coarser towards the northern ends of Culburra and Warrain-Currarong, and finer towards both ends of Seven Mile Beach-Comerong Island. At Seven Mile Beach-Comerong Island, the coarsest sample was located 1.5 km north of the Shoalhaven Heads (B23) entrance (1.21 phi), but medium sands less than 1.5 phi are found up to 5 km northwards of that.

Gravelly fractions present on beach samples were found south of Kinghorn Point and represented only a very small percentage (0.2 % maximum) of the total fraction, whereas mud fraction was only observed in samples B1 and B2 near Currarong.

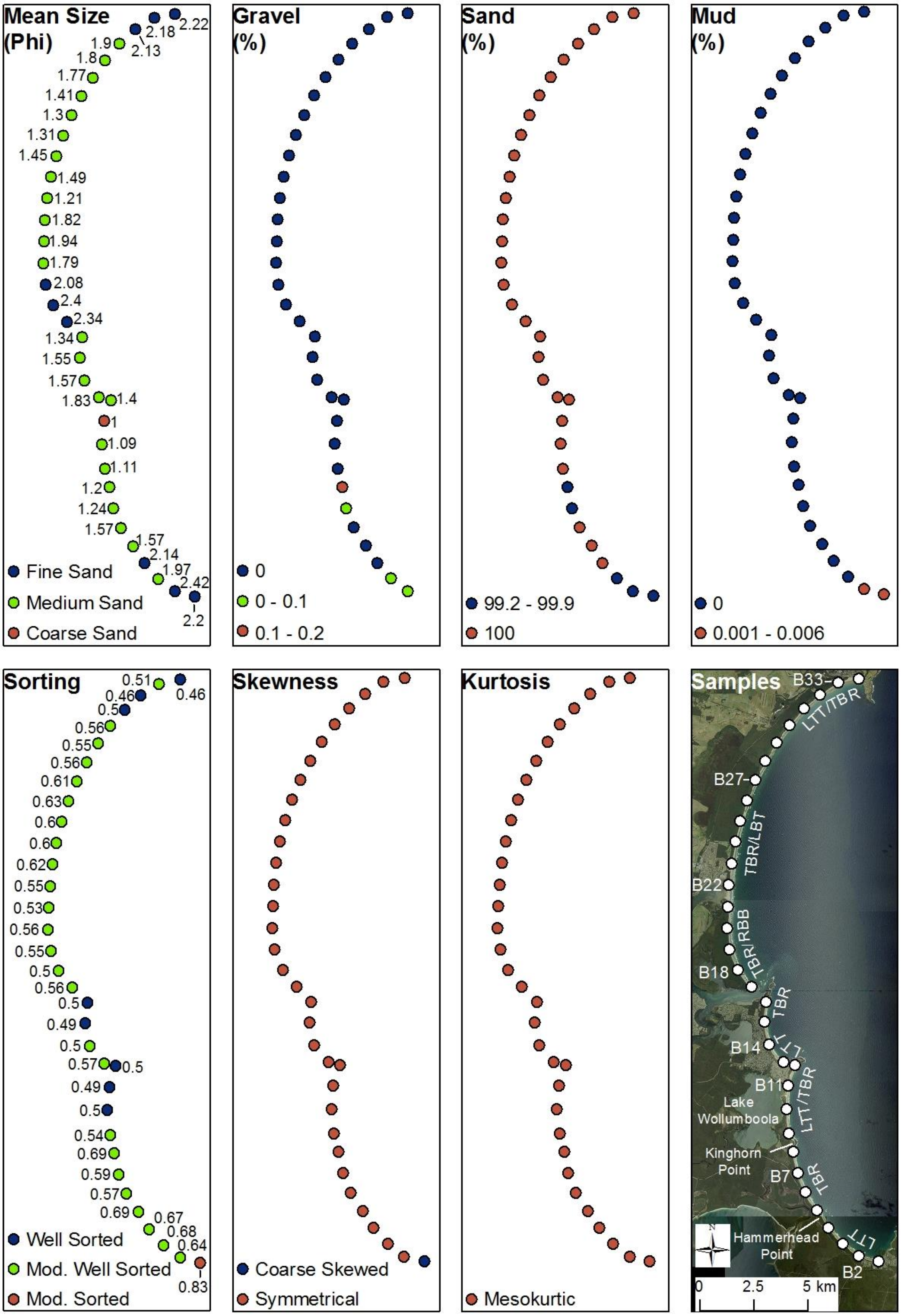

Figure 5.1 Mean grain size, percentage of gravel, sand and mud content, sorting, skewness and kurtosis of the beach samples. Sediment samples selected for further analyses, as well as four beach types (LTT =Low tide terrace; TBR = Transverse bar and rip; RBB = Rhythmic bar and beach; and LBT = Long bar through), identified by Short (2007) are labelled. Background imagery © NSW Government. Land and Property Information (LPI) 2013.

Standard deviation of beach grain size varied from 0.46 phi to 0.83 phi. Beach samples were mostly moderately well sorted, with well-sorted samples towards the northern ends of the embayments. A single moderately-sorted sample (0.83 phi) was found among the 34 beach samples and was located near Currarong (B1).

All beach samples but one were symmetrical. The symmetrical values varied from -0.05 to 0.03. The most symmetrical sample (B12) was the northernmost sample in the Warrain-Currarong embayment, but samples with high degree of symmetry were found mostly in Seven Mile Beach-Comerong Island especially north of Shoalhaven Heads and at the southern end. Sample B1 was the only coarse skewed (-0.127) sample found on the beach.

In terms of kurtosis, every single beach sample was normal (Mesokurtic) with values varying from 0.93 to 1.02. Peakedness tends to be higher towards both northern and southern ends of Warrain-Currarong, Seven Mile Beach-Comerong Island and the three northern samples at Culburra. Flatter peaks are found in the vicinity of Shoalhaven Heads.

There exists a marked decrease in size and increase in sorting in Seven Mile Beach-Comerong Island with increasing distance from Shoalhaven Heads. Therefore, the intermittently-open mouth of Shoalhaven River at Shoalhaven Heads has a profound effect on sediment distribution in that embayment, and these results are in agreement with previous works presented by Wright (1970) and Johnson (1974).

The beach samples at Seven Mile Beach-Comerong Island exhibited a similar longshore variation in grain size as disclosed by Wright (1970). He found the coarsest sample just north of Shoalhaven Heads (1.48 phi) and a decrease in grain size to both north (2.23 phi) and south (1.57 phi) ends.

Johnson (1974) analysed surficial sediments in the three embayments covered by this thesis. He found a similar pattern of longshore variation in grain size for Seven Mile Beach-Comerong Island too, with values that are closer to this thesis than Wright's. For Culburra, Johnson found a northward increase in sand size for the berm and foredune samples but a very small decrease from the sample collected halfway along the beach (1.53 phi) in relation to the one located at the northern end (1.56 phi). This small variation can be attributed either to method of analysis or sampling design and should not be interpreted as a change in average grain size over time. For Warrain-Currarong beach, the general northerly increase in grain size (Figure 5.1) corroborates the pattern observed by Johnson. He found that grain size increased from 2.56 phi at Currarong to 1.08 phi south of Lake Wollumboola and a small decrease from there to Warrain (1.44 phi).

Substantial contrasts in colour were apparent when beach samples were laid out side by side. Samples were brown in colour at Seven Mile Beach-Comerong Island, orange in colour at Culburra and most of the Warrain-Currarong embayment, and a brown colour again in the samples near Currarong (Figures 5.2 and 5.3). Under the optical microscope, the orange colour present in quartz sediments was seen to be iron-staining, indicating its relict origin. These sediments are thought to have accumulated in subaerially-exposed environments at times when the sea was lower and associated with oxidizing conditions (Stanley et al., 2000) or might have originated while the sediment was on the inner shelf (Pilkey et al., 2011).

The contrast in colour, as well as the difference in grain size and sorting, suggests different provenances for the modern beach sands of the Shoalhaven coastal compartment. Sands of fluvial-estuarine origin dominate modern Seven Mile Beach-Comerong Island, whereas reworked shoreface sands constitute the modern beaches of Culburra and Warrain-Currarong beaches. This fact also indicates the unlikelihood of sediment bypasss between Seven Mile Beach-Comerong Island and Culburra Beach, and therefore, determines that the budget of these closed secondary compartments are independent from each other.

Figure 5.4 shows selected examples of SEM images of individual quartz grains present in the 1-2 phi fraction in the analysed beach samples. Considerable variation in roundness of grains and their degree of chemical weathering distinguishes the sands of Seven Mile Beach-Comerong Island from Culburra and Warrain-Currarong beaches. Sands sourced from the Shoalhaven River, discharging to Seven Mile Beach-Comerong Island, are more angular and exhibit surfaces weathered by chemical activities, suggesting that these immature quartz grains spent little time in transport after breaking down from the source rock and also that some grains are likely to have been subject to acidic estuarine conditions. Images of all 16 quartz grains analysed per beach sample are found in Appendix 6.

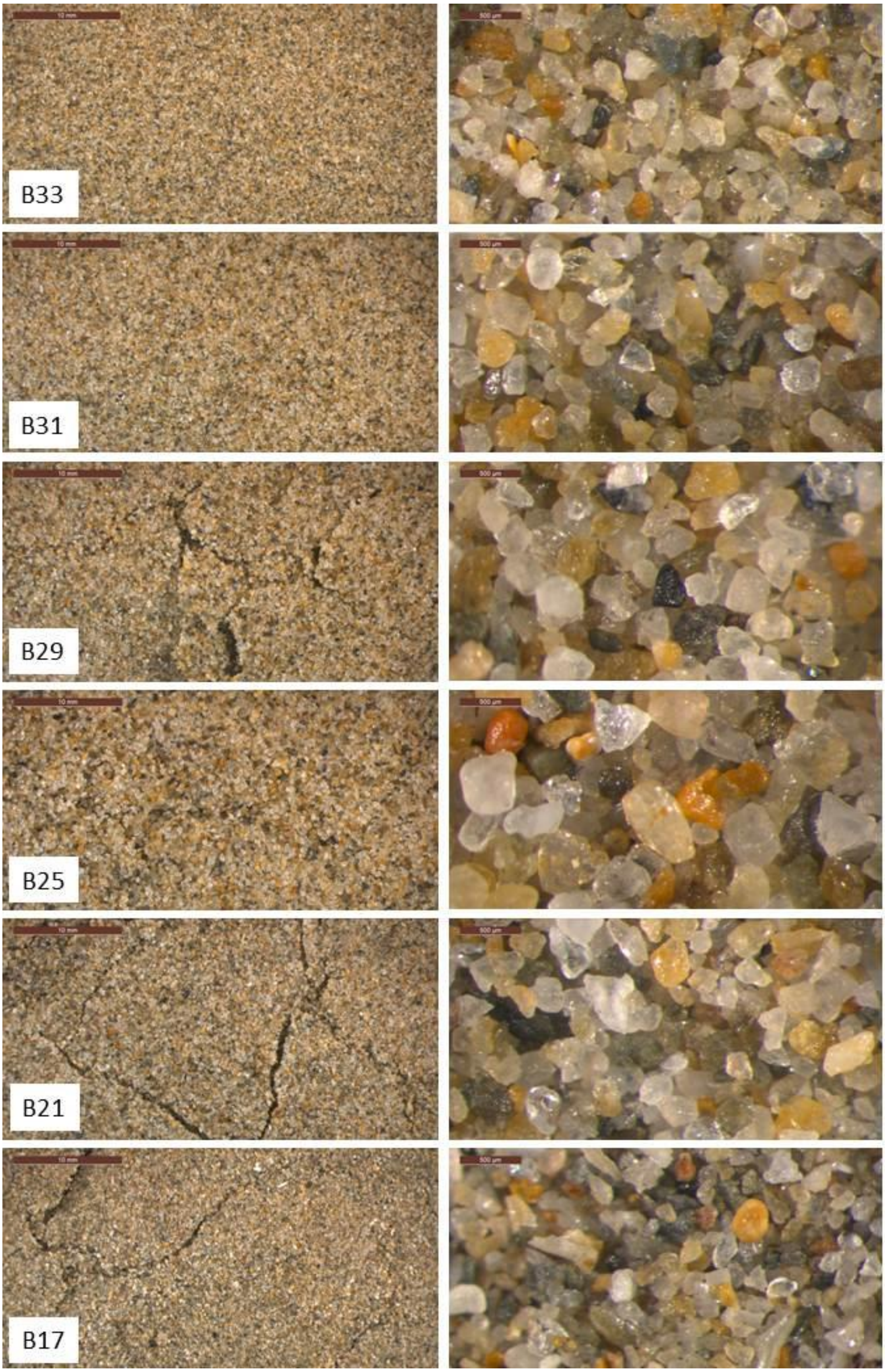

Figure 5.2 Optical microscopic photos of beach sands of Seven Mile Beach-Comerong Island from north (top) to south (bottom) at 3x (left) and 40x (right) magnification. Scale bar in upper left on left images corresponds to 10 mm and on right images corresponds to 500 µm.

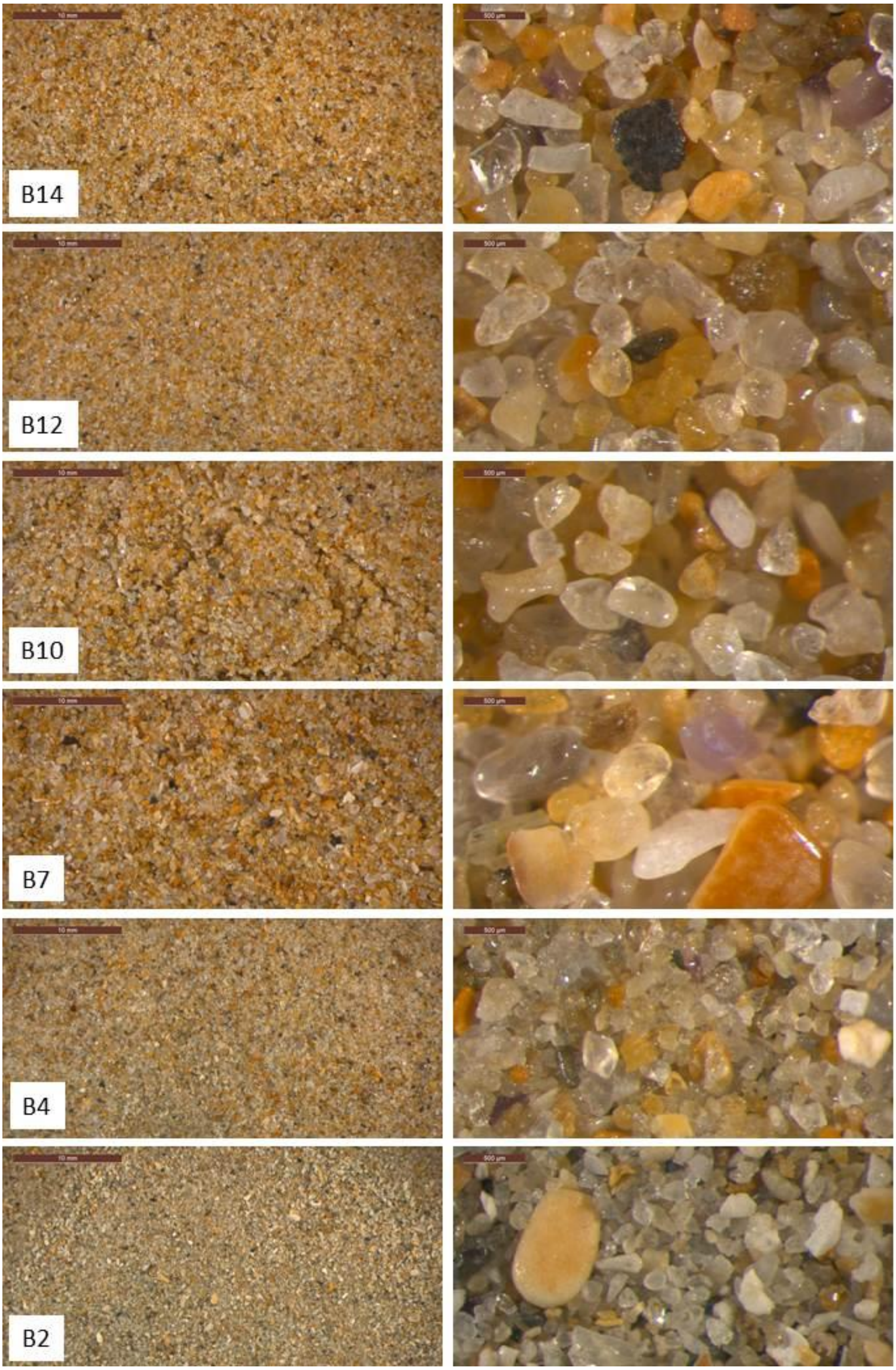

Figure 5.3 Optical microscopic photos of beach sands of Culburra and Warrain from north (top) to south (bottom) at 3x (left) and 40x (right) magnification. Scale bar in upper left on left images corresponds to 10 mm and on right images corresponds to 500 µm.

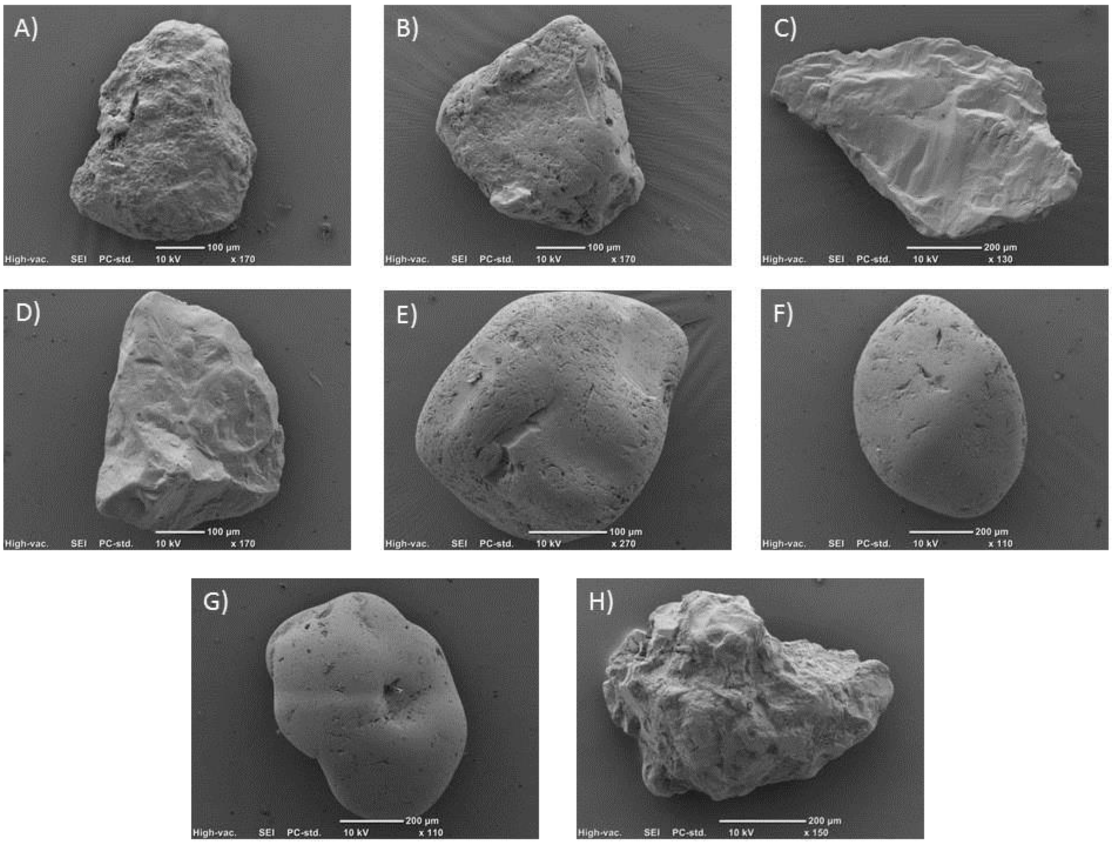

Figure 5.4 Selected examples of SEM images of quartz grains in the 1-2 phi fraction in beach samples. A) Sample B33 located at Gerroa; B) Sample B27 located 5 km north of Shoalhaven Heads; C) Sample B22 located at Shoalhaven Heads; D) Sample B18 located at Comerong Island; E) Sample B14 located at Culburra; F) Sample B11 located at Warrain; G) Sample B7 located between Kinghorn Point and Hammerhead Point; and H) Sample B2 locted at Currarong. Images of all 16 quartz grains analysed in each beach sample are found in Appendix 6.

Quartz grains observed at Gerroa (B33) were considered angular to sub-rounded and sphericity was high in most of the 16 grains. Fresh surfaces were a common feature in 6 out of the 16 analysed grains, whereas chemical weathering was observed on most of them (Figure 5.4a). Further south at B27 (Figure 5.4b), grains were mostly highly spherical and rounded to angular. Fresh surfaces were present in only a few grains, whereas chemical weathering was observed in most of them.

At Shoalhaven Heads (B22), grains had low sphericity and were very angular to sub-angular. Some of the grains showed signs of strong chemical weathering, whereas others had fresh surfaces (Figure 5.4c). The grains present on the beach at Comerong Island (B18) were slightly more spherical (Figure 5.4d) than the ones adjacent to Shoalhaven Heads (B22) (Figure 5.4c), but roundness and chemical weathering was similar.

As anticipated, more angular and spherical grains with more fresh surfaces were observed in the sands near Shoalhaven Heads than further away from the river mouth, indicating that sand delivered from the river is reworked towards the north and also onto Comerong Island. No pattern of chemical weathering alongshore could be discerned for this embayment. However, some of the quartz grains on Seven Mile Beach-Comerong Island had chemically weathered surfaces very similar to those observed on the grains in the lower estuary (Figure 4.16c to f).

The grains present in the sample at Culburra (B14) had low to medium sphericity; roundness varied from rounded to sub-angular, however most grains were sub-rounded (Figure 5.4e). Chemical weathering was absent or very light. Polished surfaces were present in most of the grains.

At Warrain (B11), grains were well-rounded to sub-rounded and had mostly low to medium sphericity. Polished surfaces were present in most of the grains (Figure 5.4f). The sample analysed between Kinghorn Point and Hammerhead Point (B7) (Figure 5.4g) had sphericity similar to, but more polished surfaces than, B11 (Figure 5.4f). Roundness varied from sub-rounded to rounded. Quartz grains at Currarong (B2) (Figure 5.4h) were very different from grains in both B11 (Figure 5.4f) and B7 (Figure 5.4g). Sphericity varied from low to high and roundness was angular to rounded. Only 3 out of 16 grains had rounded and polished edges, whereas chemical weathering could be observed in the remaining grains.

Looking at the quartz grains from Culburra and Warrain-Currarong beaches, especially in samples B14 (Figure 5.4e), B11 (Figure 5.4f) and B7 (Figure 5.4g), it is clear how different they are from the embayment to the north. Grains were much more rounded and spherical suggesting very mature sediments that were reworked considerably. This corroborates the previous observation of different sediment types between Seven Mile Beach-Comerong Island and the beaches of Culburra and Warrain-Currarong. The chemical weathering observed in some grains taken from sample B2 (Figure 5.4h) located at Currarong, as well as the southward transition in sediments from orange to brown colour (Figure 5.3) and the decrease in sorting (Figure 5.1) also suggests that some sediment contribution from the nearby creek may occur.

5.3 Mineralogy

Beach sediments were characterised in terms of mineral composition using X-ray diffraction (XRD). As expected, quartz, the most resistant of the common terrigenous rock-forming minerals to both chemical weathering and mechanical abrasion, is the most abundant mineral found among most of the analysed beach samples (Figures 5.2 and 5.3) with concentrations of 58.6-88.1 % (Table 5.1).

Feldspars were present in all samples but were more abundant in Seven Mile Beach-Comerong Island (8.7-9.7 %) than in the other two embayments (4.1-6.5 %). Feldspars are the most abundant rock-forming minerals in the Earth's crust. However, feldspars are much less resistant to both chemical weathering and mechanical abrasion than quartz, and therefore, beaches that are rich in feldspar tend to be close to the source rock from which the feldspar is derived (Pilkey et al., 2011). Orthoclase was the most abundant (1.6-4.2 %) of the feldspars in all samples but albite was apparent in B14 (1.8 %). Labradorite was absent in B14, B11 and B7, but reached 2.1 % in sample B2, located further south. Microcline was present in all samples and its concentration varied from 0.7 % at B14 to 2.2 % at B22. In the case of Seven Mile Beach-Comerong Island, the high feldspar content is derived from the feldspathic-rich rocks of the Berry Formation and possibly the granites of the Lachlan Fold Belt that occur in the Shoalhaven catchment.

Table 5.1 Mineralogy of beach surficial sediments (wt. %) of size fraction finer than 0 phi. Feldspars include orthoclase, albide, labradorite and microcline.

Sample	Chi square	Quartz	Feldspars	Calcite	Mg Calcite	Aragonite	Muscovite	Illite	Kaolinite
B33	2.8	84.4	9	0.4	0.6	0.6	1.9	1.8	1.2
B27	2.74	88.1	8.8	0	0.1	0	0	2.4	0.5
B22	2.71	87.9	8.7	0	0.4	0	0	2.3	0.7
B18	2.98	85	9.7	0.1	0.6	0	2.2	1.6	0.8
B14	2.66	77.9	4.1	2.7	3.6	10.1	0	1.3	0.3
B11	2.66	86.3	5.8	1.4	1.1	4.6	0	0.3	0.5
B7	2.79	79.3	4.8	2.9	3.9	7.5	0	1.3	0.3
B2	2.33	58.6	6.5	7.4	16.1	9.1	0	1.9	0.3

Carbonates were almost absent in Seven Mile Beach-Comerong Island (B33, B27, B22 and B18) sands but constitute a significant portion (16.4 %) of sample B14, located at Culburra, as well as, in Warrain-Currarong samples, where abundance increased southwards, from 7.1 % at B11 to 32.6% at B2. Aragonite was the most abundant of the carbonates in B14 (10.1 %), B11 (4.6 %) and B7 (7.4 %), whereas Mg calcite was the highest at B2 (16.1 %). The high abundance of aragonite in Culburra and Warrain-Currarong samples is associated to the existence of a number of different marine organisms, including gastropods and bivalves that inhabit the submerged rock reefs and nearshore sands between Penguin Head and Beecroft Peninsula.

Clay minerals were present in the beach samples in the form of Muscovite, Illite and Kaolinite. Clay mineral content varied from 2.9 % (B27) to 4.9 % (B33) at Seven Mile Beach-Comerong Island, and was less than 2.2 % in the beach samples of Culburra and Warrain-Currarong. At Seven Mile Beach-Comerong Island, the highest content of clay minerals was associated with the decrease in mean grain size. Samples composed of fine sands, located near Gerroa (B33) and Comerong Island (B18), had approximately 2 % more clay minerals than medium sand size samples B22 and B27. Hence, the higher clay mineral content observed at the two opposite ends of this tertiary level compartment is not necessarily related to erosion of the Westley Park Sandstone that forms Black Head or the Wandrawandian Siltstones that forms Crookhaven Heads. Muscovite was only detected in B33 (1.9 %) and B18 (2.2 %), where it constituted the most abundant among the clay minerals. Illite was present in all samples and was the most abundant of the clay minerals in five of the eight samples. Kaolinite was also present in all samples but its concentration was lower than Illite, apart from sample B11, where it was slightly higher (0.5 %).

In general terms, two types of sands exist in the Shoalhaven coastal compartment based on the mineralogy of beach samples. The feldspar and clay mineral -rich, carbonate-deficient sands of Seven Mile Beach-Comerong Island, and the feldspar and clay mineral-deficient, carbonate-rich (aragonite) sands of Culburra and Warrain-Currarong beaches.

No distinction could be made between the samples collected at Culburra (B14) and the two northernmost samples at Warrain-Currarong (B11 and B7). However, sample B2, located at Currarong showed a much higher abundance of all forms of carbonates, and slightly higher feldspar content than samples B7 and B11. Although the increase in carbonate content can be associated with the extensive rocky reefs of Beecroft Peninsula, the increase in feldspar could be an indicator of the influence of Currarong Creek delivering sediments to the beach, also suggested by the chemically-weathered quartz grains in sample B2 (Figure 5.4h). These differences indicate a third type of sand for the Shoalhaven coastal compartment between Currarong and Hammerhead Point, and a possible significant source of sediments to the secondary compartment of Warrain-Currarong.

5.4 Beach-Barrier morphology

Three different barrier types have developed in the Shoalhaven coastal compartment (Figure 5.5) over the course of the Holocene. One at each tertiary level compartment: a prograded barrier system at Seven Mile Beach-Comerong Island, a receded barrier at Culburra and a stationary barrier at Warrain-Currarong.

The Holocene barrier system adjacent to Seven Mile Beach-Comerong Island is 17 km long. Interpretation of LiDAR shows it to be composed of a series of 38 inner-ridges to the outer-foredune ridge (Figure 5.6). These ridges were deposited over a period that started around 7,500 years BP according to calibrated radiocarbon dating published in the early 1980s, as the shoreline prograded 1,350 m seawards.

The barrier behind Seven Mile Beach-Comerong Island occupies an area of 15.2 km^2 and an estimated volume of approximately 88,000,000 m^3 above 0 m (AHD). In general terms, the inner/older ridges are higher than the outer/younger ones (Figure 5.6) suggesting that either more sediment or time was available to construct the ridges or that less accommodation space existed and deposition would have happened in a restricted space when compared to the outer ridges. Individual ridges are also higher near Shoalhaven Heads than at both north (Gerroa) and south (Comerong Island) ends. One can envisage that the reworking of the marine sediments during the last transgression associated with new contributions of sediments from the estuary via Shoalhaven Heads have contributed to this trend that is in contrast to what is observed in other prograded barriers in NSW where the northern end develops higher ridges that may evolve into transgressive dunes (e.g. Newcastle Bight). A combination of its geologic inheritance, orientation to the general waves and wind climate, associated with its varying riverine supply of sediment at Shoalhaven Heads and not in the southern end of the embayment, exerts control on its morphology.

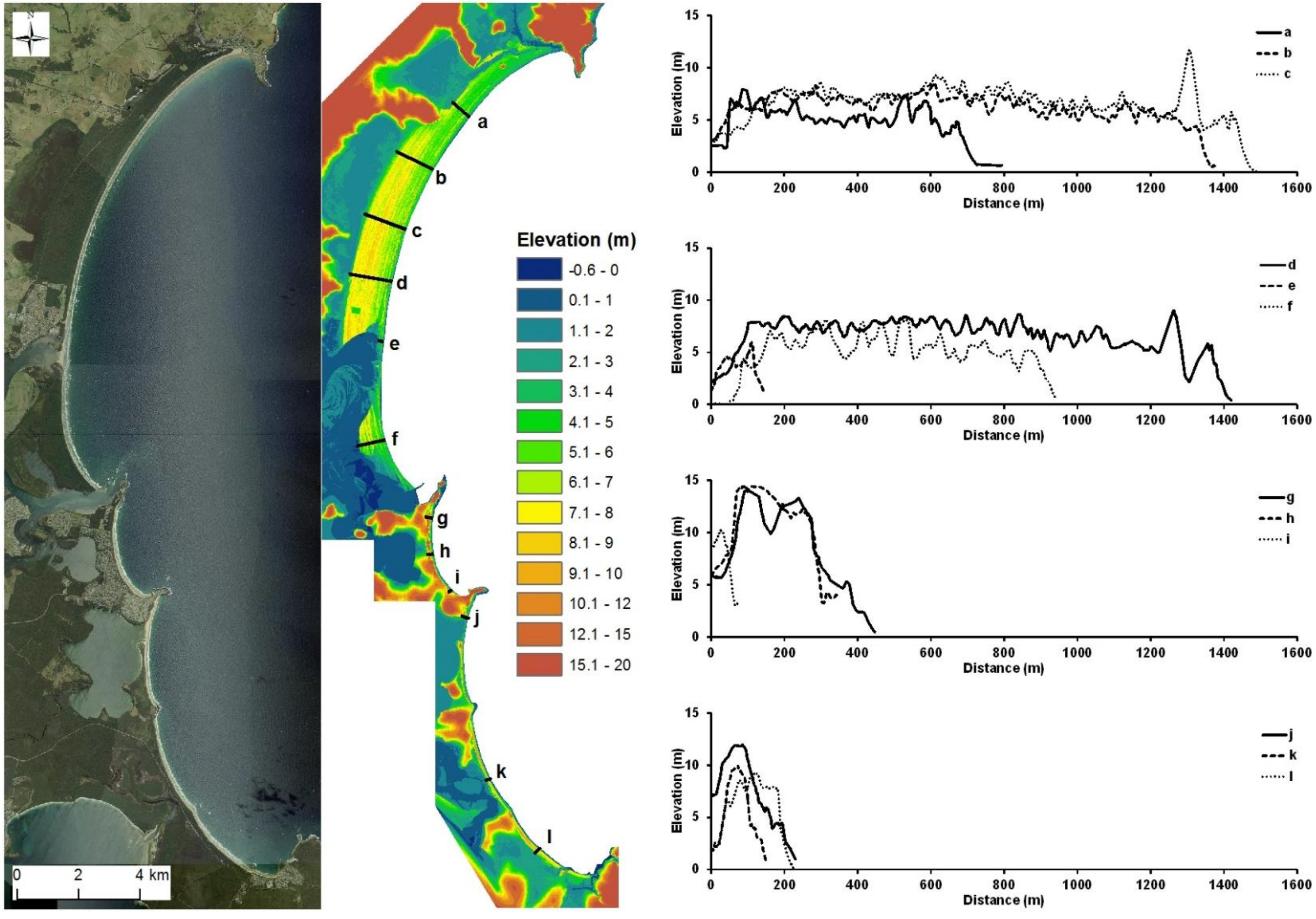

Figure 5.5 Aerial photography of the Shoalhaven coastal compartment showing the three secondary compartments (left), elevations (m AHD) derived from LiDAR data processed for ground points (middle) and cross-sections of different morphologic types of barriers (right). Background imagery and LiDAR data © NSW Government. Land and Property Information (LPI) 2013.

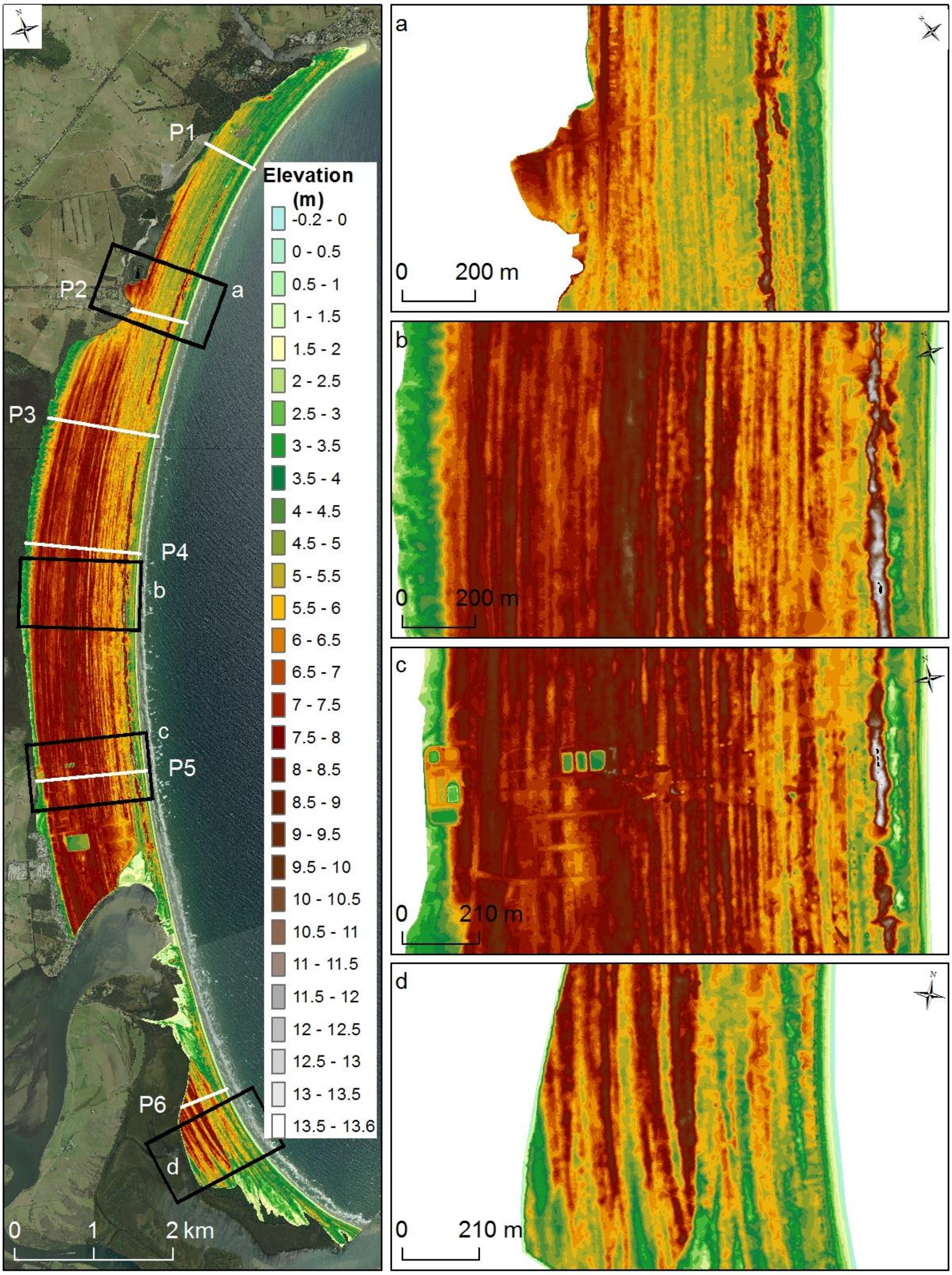

Figure 5.6 Elevations (m AHD) of Seven Mile Beach-Comerong Island beach barrier system derived from LiDAR data. Insert maps on the right show details of the ridges, whereas P1-P6 indicate the location of profiles used in Figure 5.7. Background imagery and LiDAR data © NSW Government. Land and Property Information (LPI) 2013.

The highest elevation occurs on the modern foredune, and reaches 13.6 m above AHD in the middle of the embayment (Figure 5.6b and c). This ridge decreases in height towards the south (8.8 m) and north (5.3 m) ends of Seven Mile Beach (Figure 5.6a) and reaches 6.6 m in the middle of Comerong Island (Figure 5.6d). The width of the beach-barrier system decreases toward Gerroa and Comerong Island. The innermost ridge is located 1190 m landwards from the foredune ridge at its widest. The sequence seems to continue towards Comerong Island despite the absence of this ridge due to past erosion caused by lateral migration of the river.

Ridge alignment, continuity and height trends corroborate previous conclusions that past processes were significantly similar to those in the present, and that the Shoalhaven River is the principal contributor to barrier progradation (Wright 1970). However, mineralogical information presented by Wearne (1984) for samples located in the vicinity of profiles P1, P3 and P5 (Figure 5.6), indicates a consistent and steady increase in lithics (feldspar and rock fragments) and corresponding decrease in quartz seawards along P3 and P5, and that sediments along profile P1 have a similar mineralogy to those from Seven Mile Beach. These findings suggest a varying importance of marine and fluvial sediment contributions during barrier development, with the former acting during barrier initiation and the river exerting an increasing influence on barrier progradation by supplying relatively increasing amounts of fluvial sediment to the yonger ridges.

Based on LiDAR data, the formation of the Shoalhaven deltaic-estuarine plains (Woodroffe et al., 2000, Umitsu et al., 2001), the ^{14}C dating by Thom et al. (1981), the mineralogy of barrier sediments in Wearne (1984), and Shepherd's model (1987) of foredune and beach ridge development, that proposes that the rate of coastal progradation or retreat, as determined by the sediment budget, can be the dominant influence upon foredune morphology, and conversely that profiles across beach ridge systems may provide a useful guide to past and future coastal trends, four different periods of barrier formation can be identified (Figure 5.7). Six profiles (P1–P6) have been selected to explain the different periods and their relationship to sediment sources.

Period 1 initiated around 6,500 years BP as indicated by ^{14}C dating in the western core of profile 5 (Figure 5.7), and a strong sediment supply of marine source, as demonstrated by the low feldspars content analysed by Wearne (1984), allowed the development of a high coastal barrier of approximately 8 m (AHD) in elevation. After barrier initiation, this period was characterised by a slowly prograding coastline that required a longer period before each foredune is succeeded by a younger one, enabling each ridge to develop to a greater size and the average height of the barrier to be high. This first period happened during restricted accommodation space limited by the high elevation area near P2 (Figure 5.6a) and demanded a continuing supply of marine sediments from the shoreface. Some sand bypassing probably occurred to the north but barrier development was in its infancy there. Assuming that the beach profile remained constant, during period 1, the barrier accumulated approximately 41 % (36,180,000 m^3 of sand) of today's barrier volume above 0 m AHD.

Period 2 was characterised by the expansion of the barrier system to the north and therefore an increase in accommodation space. Coastal progradation was still slow as more space alongshore became available, but could have picked up by the time that the estuarine basin infill was largely complete by 3000 years BP (Woodroffe et al., 2000) and fluvial sediments became more important for barrier development. The mineralogical data presented by Wearne (1984) supports the idea of an increasing fluvial influence on barrier accretion after 4000 years BP, as indicated by the lithics (feldspar and rock fragments) content increase along profiles 3 and 5 (Figure 5.7). Sediment supply from marine sources was probably reduced compared to the previous period as the shoreface became deeper and more concave. The accumulation of approximately 14 % (12,060,000 m^3 of sand) of today's barrier volume above 0 m AHD occurred during Period 2.

Period 3 marks the further expansion of the barrier system both north, towards Gerroa, and south, towards Crookhaven Heads, increasing the accommodation space availability. This period initiated around 2200 years BP as indicated by ^{14}C dating in the middle core of profile 1 (Figure 5.7). The difference between the height of the ridges and swales is greater to the north of Shoalhaven Heads (Profile 5). However, an average decrease in the height of the barrier was observed, when compared to the previous two periods. This is indicative of rapid growth of successive foredunes with each new foredune depriving the landward older dune of its sand supply (Shepherd, 1987).

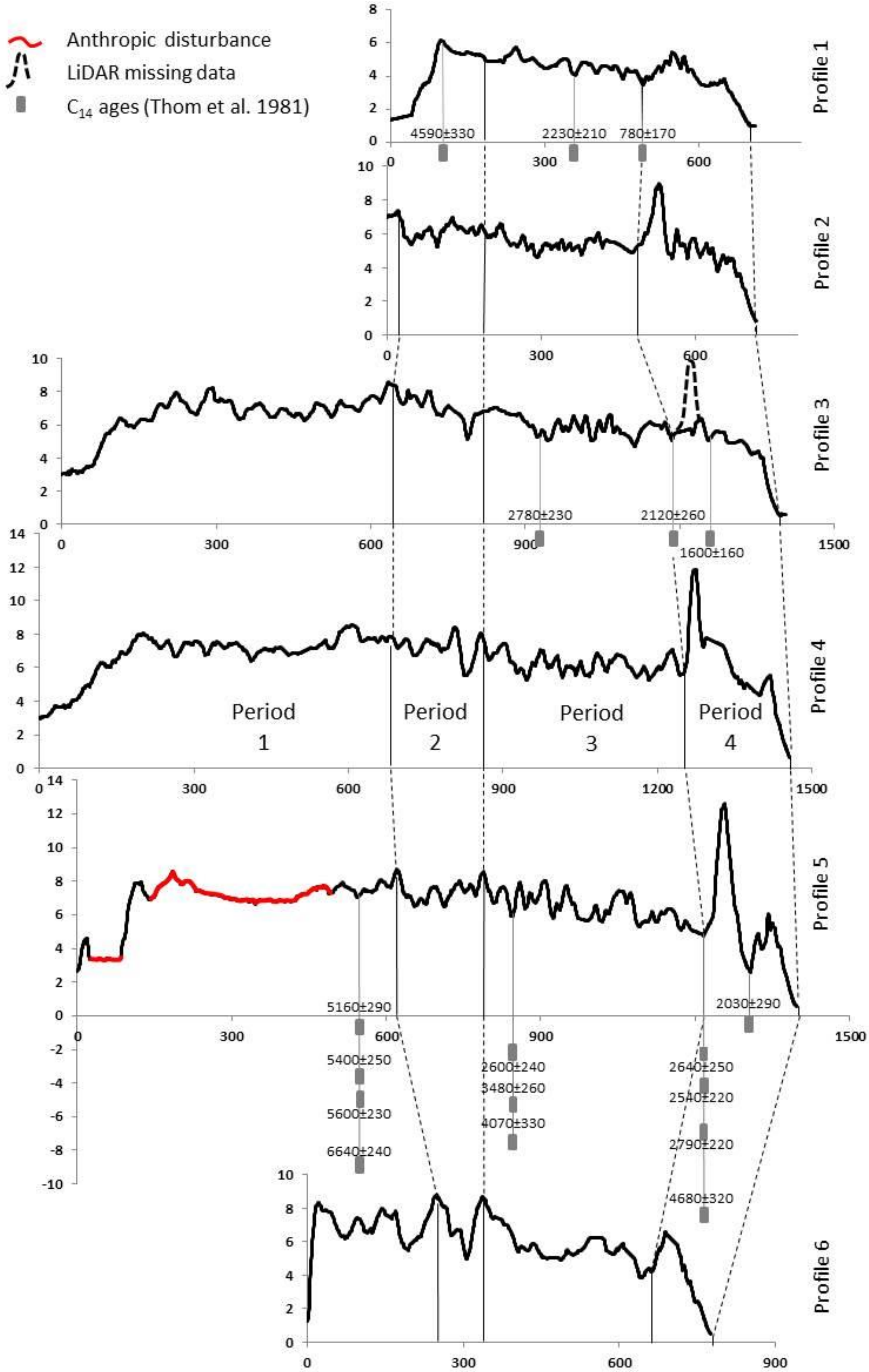

Figure 5.7 Four different periods of formation for Seven Mile Beach-Comerong Island beach barrier system. Profiles extracted from LiDAR data and locations (P1- P6) are shown in Figure 5.6. P1, P3 and P5 correspond to profiles in Thom et al. (1981) and Wearne (1984). 95 % confidence interval on calibrated ^{14}C age (Thom et al., 1981).

This rapidly prograding period can be associated with an increase in the fluvial supply of sediments to the coast after most of the estuarine had infilled, as indicated by the lower values of quartz and higher values of lithics (feldspar and rock fragments) obtained from samples located along profiles 1, 3 and 5 (Wearne, 1984), despite the drier climatic condition experienced in southeastern Australia in the last 2,500 years BP, as indicated by Fitzsimmons and Barrows (2010). A re-activation of the sediment supply from a marine source, by process of forced regression caused by the late-Holocene relative sea-level fall may have contributed to this rapid progradation (Kinsela et al., 2016). Approximately 29 % (25,530,000 m^3 of sand) of today's barrier volume above 0 m AHD accumulated during this period.

Period 4 started after 780 years BP, as indicated by ^{14}C dating in the eastern core of profile 1 (Figure 5.7) and the accumulation of approximately 16 % (14,280,000 m^3 of sand) of today's barrier volume above 0 m AHD occurred during this period. According to Shepherd (1987), a large foredune observed along the barrier, like the one that reaches 13.6 m at profile 5, is the result of a barrier that prograded rapidly and became stable or very slowly receded. However, mineralogical data presented by Wearne (1984) supports the idea of continuity of fluvial supply as indicated by the lithics (feldspar and rock fragments) content increase at profiles 3 and 5 (Figure 5.7), whereas the remaining centuries of smooth regression of sea-level to present level, suggests that sediment supply from marine sources probably continued to present day. Regardless of how this high foredune was formed, at least three incipient foredunes (newly developing foredune forming within pioneer plant communities) can be observed (profiles 2 and 3) seawards of the highest one, indicating that the coastline is continuing to rapidly prograde.

Another interesting aspect of Figure 5.7 is that during periods 1 and 2 the average height of the barrier remained constant, whereas the following periods witnessed a gradual fall in height. This may be related to the fact that the culmination of the Holocene marine transgression was followed by sea-level highstand of +1.5 m that lasted until approximately 2000 years ago, followed by a relatively slow and smooth regression to present level (Sloss et al., 2007). This aspect, however, needs to be investigated further to check whether this gradual fall is detectable in other prograded barriers on the east coast of Australia.

There are many important aspects related to understanding the evolution of Seven Mile Beach-Comerong Island at a geologic time scale that differ considerably from the short-time scale sediment budget of this thesis. The main one is probably to understand whether the roles played by storm events, fluvial and shoreface supply in the past, are still active in the present. Storms are capable of eroding the beach face and foredune over time scales of hours to days. The fluvial signature can be used to infer major river discharges events, and the shoreface supply, can sustain shoreline progradation, if sand supply from the shoreface dominates over littoral sediment losses (Cowell et al., 2001). Shoreface supply, for instance, contributed 80 % of the sand for barrier growth at Tuncurry (340 km north of Nowra), between 6 ky BP and present (Kinsela et al., 2016). Whereas no specific shoreface supply rates can be calculated for Seven Mile Beach-Comerong Island, the recognition of an ongoing potential shoreface source could offset the budget and explain the observed accretion on the beach.

The barrier at Culburra (Figure 5.8) extends for 3.6 km alongshore, occupies an area of 0.61 km^2 and a volume of approximately 4,650,000 m^3 above 0 m (AHD). Due to the infrastructure and development that ocurred after the 1940's, the back-barrier limit and therefore the barrier width is somewhat hard to identify. However, LiDAR data shows that the barrier at Culburra reaches approximately 15 m height in the north and middle, reducing to 1/3 of its height to the south. The barrier is also wider in the northern end compared to its southern counterpart. The second zoomed in area from the north (Figure 5.8b), shows the large blow out that occurred in the 1970's.

The barrier at Culburra was considered a receded barrier by the NSW Public Works Department (PWD, 1980) based on four main aspects: a narrow barrier composed of a single foredune ridge; the facies boundary between the back-barrier and barrier sand lies near the present shoreline; the back-barrier sand is narrow and thin; and the barrier sand unit appears to have over-ridden the back-barrier sand unit and possibly an estuarine mud unit, however, the dark coloured material exposed in the surf zone, in the centre of the beach, in 1980, could not be proven to be a back-barrier, swamp or estuarine deposit, and therefore, the interpretation as a receded barrier could not be validated.

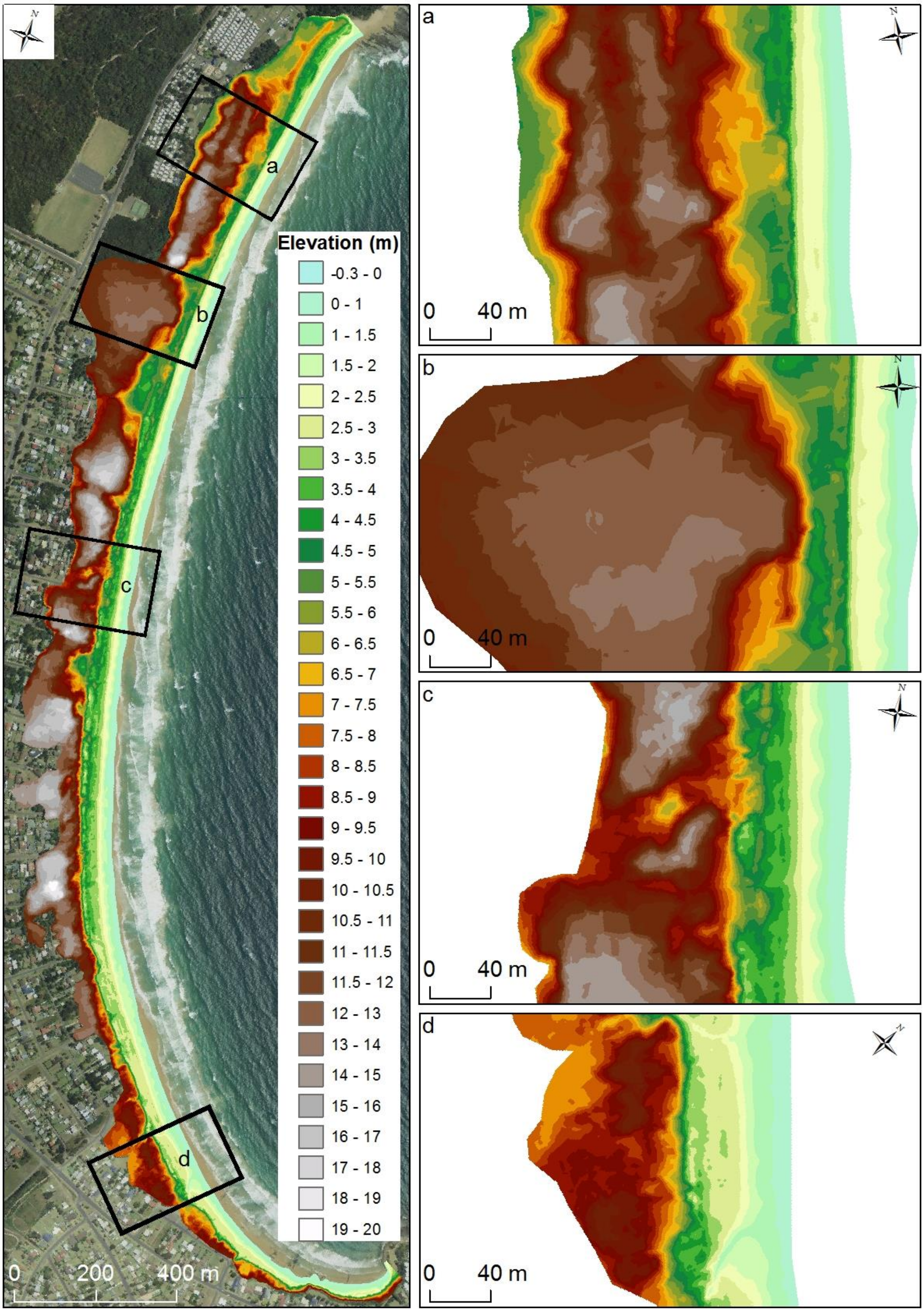

Figure 5.8 Elevation (m AHD) of Culburra beach barrier system derived from LiDAR data. Inset maps on the right show details of the receded barrier. Background imagery and LiDAR data © NSW Government. Land and Property Information (LPI) 2013.

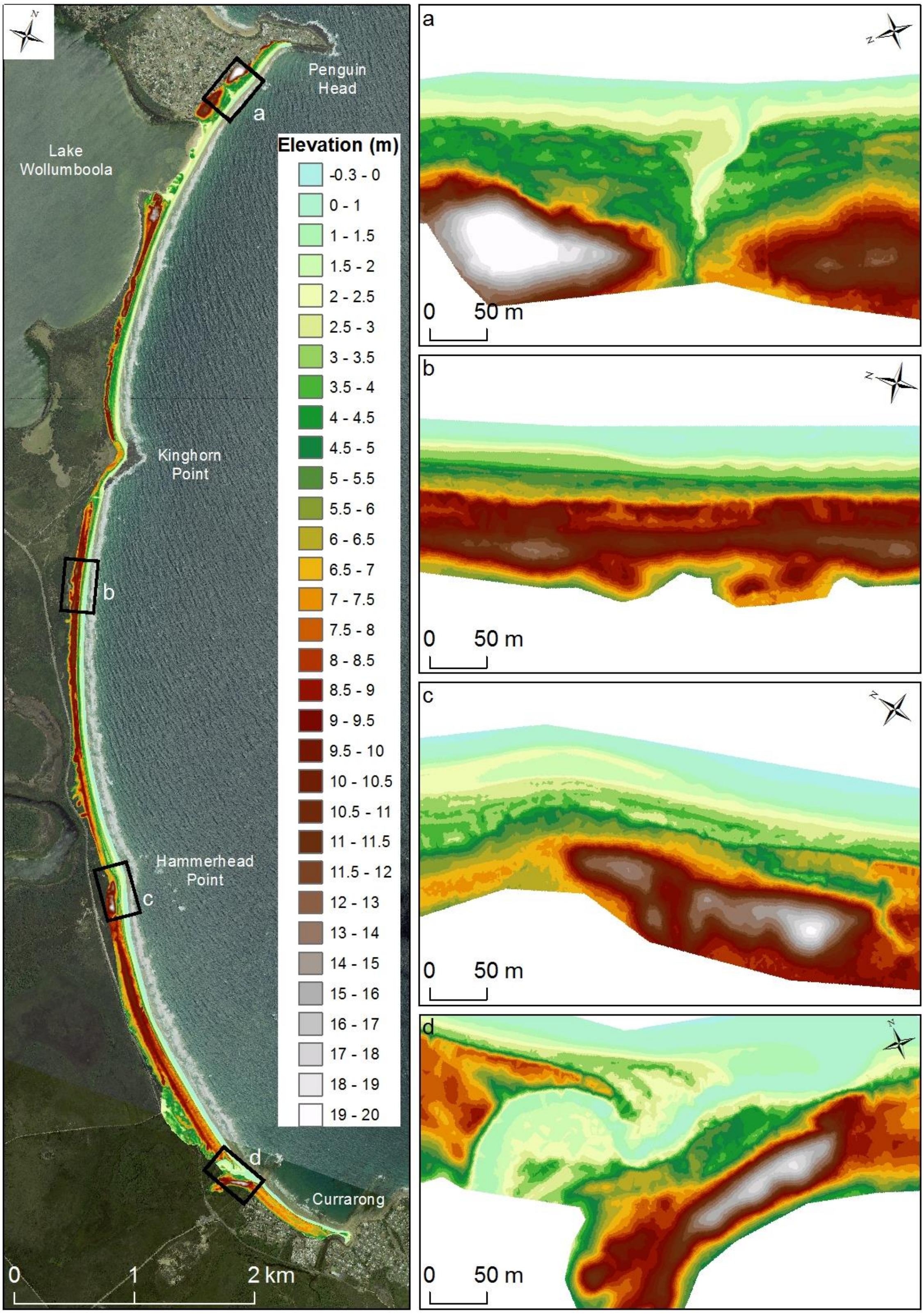

Figure 5.9 Elevation (m AHD) of Warrain beach barrier system derived from LiDAR data. Inset maps on the right show details of the stationary barrier. Background imagery and LiDAR data © NSW Government. Land and Property Information (LPI) 2013.

The stationary barrier of Warrain-Currarrong (Figure 5.9) occupies an area of 1.7 km^2 with a volume of approximately 9,580,000 m^3 above 0 m (AHD). It reaches 26.3 m above 0 m (AHD) by 200 m in width, at the northern end, north of Lake Wollumboola entrance.

The barrier extends for 11.3 km alongshore, and between Penguin Head (north) and Currarong Creek (south), two low rocky reefs subdivide the embayment: Kinghorn Point and Hammerhead Point. These rocky reefs are covered in sand by the barrier and are only exposed in the subaerial and subaquaous beach, however, several other barrier interruptions occur along the way. The major one occurs when the beach berm at Lake Wollumboola is breached. Another discontinuity caused by a creek occurs on the southern part next to Currarong (Figure 5.9d). Two other smaller creeks are also found, one located south of Penguin Head on the northern end (Figure 5.9a) and another one south of Hammerhead Point (Figure 5.9c). These discontinuities cause the accumulation of sand, and barrier elevation is higher near these interruptions.

5.5 Beach behaviour at decadal time scale

Moruya (McLean and Shen, 2006, McLean et al., 2010) and Narrabeen-Collaroy (Harley et al., 2015) are examples of long-term monitored beaches in NSW. However, such consistent data collection has never been acquired for beaches within the Shoalhaven compartment. In the absence of such, historical aerial photography is commonly employed to quantify beach recession and accretion. Hence, photographic evidence of beach behaviour over past decades will be used in the last chapter of this thesis to calculate the volumetric change experienced at each beach, and therefore, the coastal budget.

The shoreline displacement for Seven Mile Beach-Comerong Island from December 1948 onwards based on the vegetation line, digitised from georeferenced aerial photographs at different scales is shown in Figure 5.10. Cross-sections are plotted at the same locations as the monitoring at short time scale, shown in Figure 2.7. The results presented below should be treated with caution, as the measurement of the seaward boundary of dune vegetation may be affected by factors other than coastal erosion, and, therefore, trends in the movement of the vegetation line may not always reflect coastal erosion and accretion (Hanslow, 2007).

The shoreline on the northern part of the embayment (SH1), in August 1963, was located 54.1 (±10.4) m landwards of its December 2013 position. In the 1970's, the south coast of NSW was damaged severely after the destructive effects of storms in 1972 (Chapman et al., 1982), 1974 (Bryant and Kidd, 1975) and 1978 (Callaghan and Helman, 2008). During the 1970's storms, the coastline retreated approximately 16 m, and then linearly accreted 70.4 (±8.6) m after January 1982. Further south (SH2), the coastline experienced the greatest displacement in the embayment. Back in August 1963, the shoreline was located 97 (±14.1) m landwards of its present location, but quickly accreted approximately 33 m by July 1977. The next aerial photograph taken in January 1982, showed a major retreat of approximately 27 m and it then progressively accreted 91 (±3.6) m to its December 2013 position. It is interesting to note that only the 1978 storm produced a major retreat at SH2, whereas the 1974 storm did not.

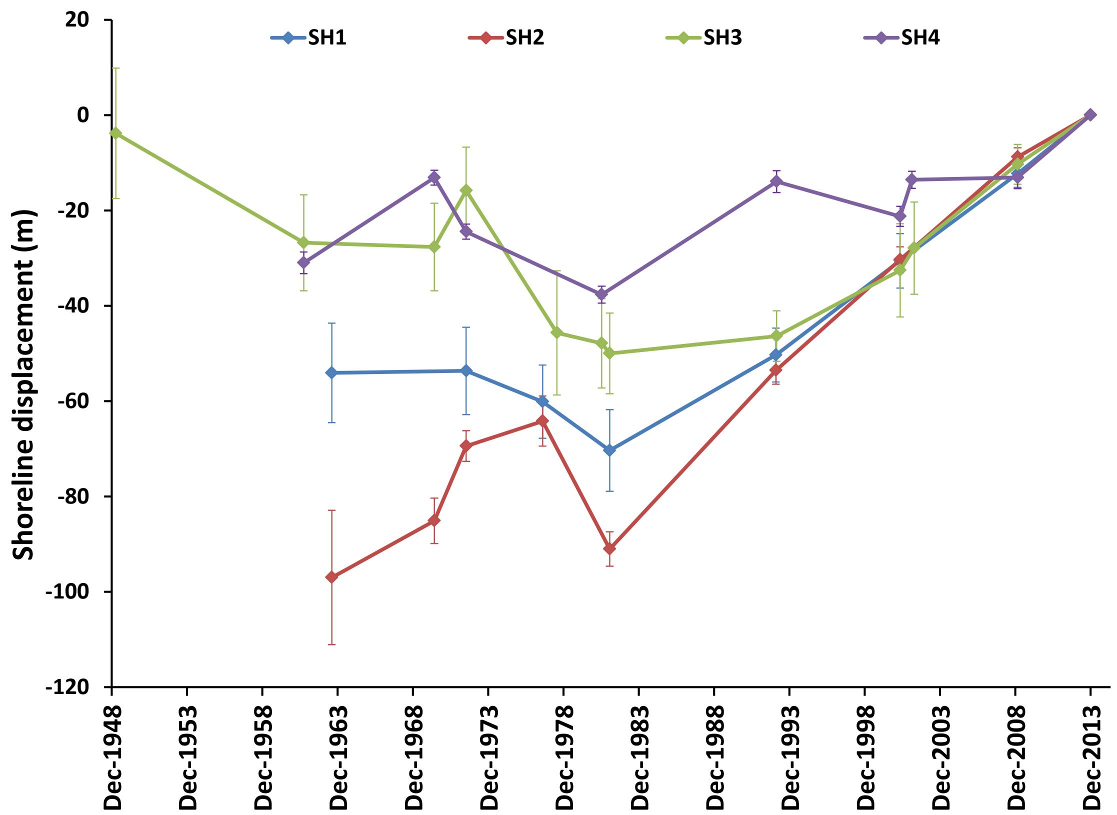

Figure 5.10 Seven Mile Beach-Comerong Island mean shoreline displacement plotted with respect to its position in December 2013 based on historical aerial photographs. Vertical bars represent standard deviation based on 5 50-m spaced cross-sections along the beach. Location of profiles is shown in Figure 2.7.

Near Shoalhaven Heads (SH3), the shoreline position in April 1949 was located very close to its position in December 2013. Back at that time no Surf Life Saving Club (SLSC) existed there and, due to sparse vegetation, some of the youngest beach ridge alignments could be seen in the aerial photograph. In the photograph of September 1961, the shoreline had retreated approximately 23 m, remaining somewhat stable for the following decade until May 1970. The photograph of July 1972 shows an accretion of approximately 12 m and the subsequent photograph taken in July 1978 shows a retreat of approximately 30 m, followed by a another 5 m retreat by the January 1982 image, when the beach recession reached its peak. The time period up to the early 1980's for SH3 is consistent with the recession analysis performed by PWD (1982b). In the subsequent 11 years, not much progradation could be observed and the shoreline displaced seawards at a faster rate only after February 1993, similar to what was observed at SH1 and SH2.

At Comerong Island (SH4), the shoreline displacement showed the least variation in the past 52 years. In September 1961, the shoreline was 31 (±2.3) m landwards of its December 2013 position. The shoreline experienced accretion of approximately 18 m until May 1970 and erosion during the 1970's. In June 1981, the shoreline was 37.7 (±1.8) m landwards of its December 2013 location, reaching its landwardmost position. After that, the shoreline oscillated at least once in its progradation pattern to reach its December 2013 position. It is worth noting that the progradation rate (0.7 m/y) following the February 1993 photograph, was the smallest of all the four analysed sections within the Seven Mile Beach-Comerong Island embayment, and only after February 2009 did it keep pace with the other three sections.

The shoreline displacement that occurred at Culburra Beach (Figure 5.11) was very different from what occurred at Seven Mile Beach-Comerong Island (Figure 5.10). At Culburra (Figure 5.11), the northern end of the beach (CUL1) experienced the greatest variation of all three sections of the beach since December 1948. The shoreline position varied more than 68 m in the 65-year window. In December 1948 the shoreline was 61.5 (±5.2) m landwards of its December 2013 position, but quickly prograded approximately 30 m until September 1961. Then, it experienced two small oscillations until January 1982. The subsequent photograph taken in January 2002, showed another approximately 30 m progradation, 4.3 (±4.5) m landward of the shoreline position in

December 2013. By February 2009, the vegetation line accreted even further and then receded 6.6 (±3.2) m to reach its December 2013 position.

In December 1948, the middle of Culburra Beach (CUL2) was 57.2 (±15.5) m landwards of its December 2013 position. It accreted approximately 53 m at a fast rate until July 1972, and then was impacted by the 1970's storm, receeding approximately 30 m by July 1978 but partially recovered at a fast rate within the following three years. CUL2 also experienced a minor recesssion of approximately 2 m by January 1982, but slowly accreted at an average rate of approximately 0.6 m/y until December 2013.

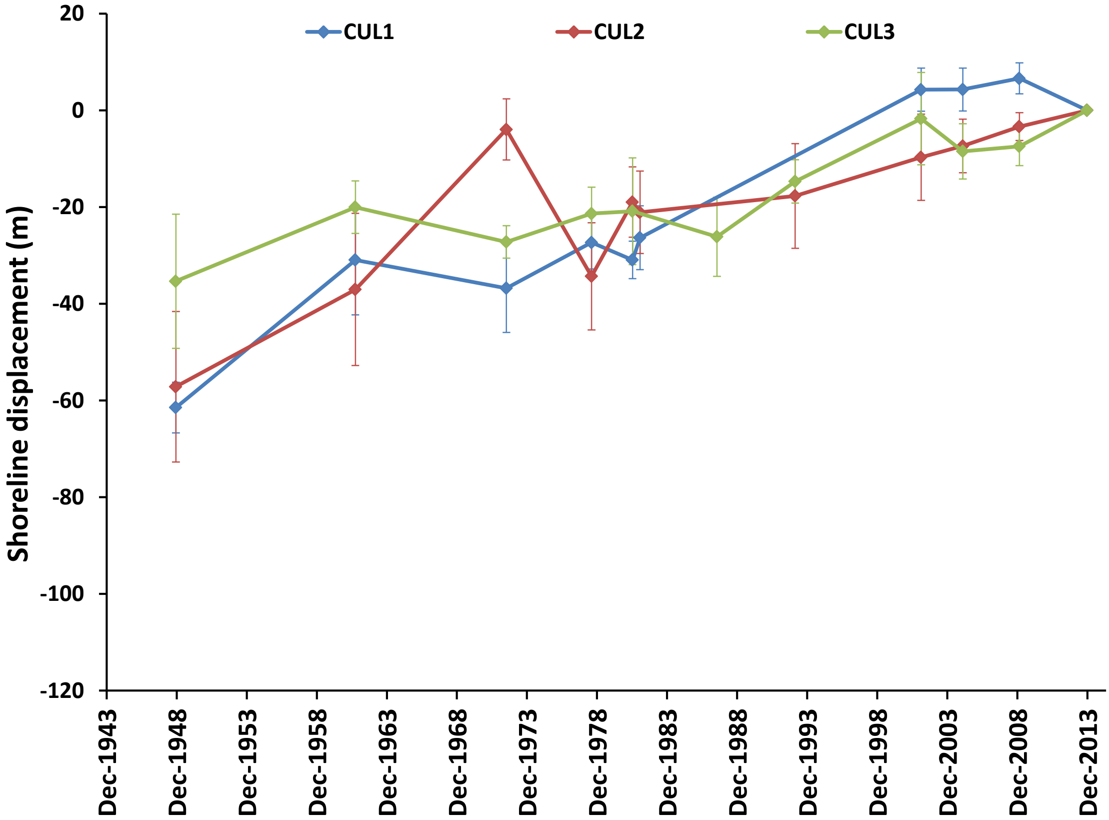

Figure 5.11 Culburra Beach mean shoreline displacement plotted with respect to its position in December 2013 based on historical aerial photographs. Vertical bars represent standard deviation based on 5 50-m spaced cross-sections along the beach. Location of profiles is shown in Figure 2.7.

The southern end (CUL3) of Culburra Beach experienced the smallest variation among the three analysed sections of the embayment. The vegetation line accreted only 35.4 (±13.9) m since December 1948, and experienced at least three small recessions on its accretion trajectory until December 2013. The first one was observed in July 1972, the second in July 1987 and the third in January 2005. In the past few years (since February 2009), the vegetation line at the southern end (CUL3) has extended approximately 7.5 (±4) m, at a faster rate than what was experienced in the middle of Culburra Beach (SH2) and contrary to the recession experienced at the northern end (CUL1).

These findings corroborate previous studies of coastal erosion at Culburra Beach between 1949 and 1978 (PWD, 1980), despite the difference in methodologies and the possible errors associated with them. The beach behaviour at decadal scale presented here, identified a continuous seawards shoreline displacement for the northern end of Culburra Beach until 1978; a seaward displacement until 1972, followed by huge landward displacement until 1978 in the middle of the beach; and a minor oscillatory pattern of seawards-landwards-seawards displacement until 1978 in the southern end of Culburra, very similar to that observed for the scarp line in cross-sections number 25, 11 and 4, respectively in the PWD (1980) report. The differences lie in the fact that the 1980 report calculated minor accretion from 1949 to 1961 and a further landward displacement (erosion) of the scarp line from 1969 to 1978 for cross section 4, whereas the present study found major seawards displacement (accretion) of approximately 15 m until 1961 and a minor accretion of approximately 6 m between 1972 and 1978, for CUL3.

It is worth remembering that no contradiction arises from the fact that a receded barrier such as Culburra accreted in the last 65 years. The general trend observed since 1948 indicates that the barrier almost continuously accumulated sand over these years, whereas the term receded barrier describes the mode of initial formation in the Roy et al. (1980) model of barrier evolution and does not necessarily predict (modern) erosinal/accretional behaviour (PWD, 1980).

Warrain-Currarong Beach experienced the shortest shoreline displacement (Figure 5.12) of the three analysed tertiary level compartments, indicating that this beach has had a slower rate of sand addition than Seven Mile Beach-Comerong Island and Culburra Beach from 1948 to 2013. The vegetation line at the northern end (WAR1) of the beach experienced the greatest progradation within this embayment. It prograded 55.1 (±9.1) m since September 1961. Previous to this date (December 1948), no displacement was observed, as the vegetation line remained relatively stable. Two oscillations happened in the analysed time, the first one was observed in the July 1978 photograph and the second one in January 2005.

The middle (WAR2) of Warrain-Currarong Beach did not accrete much after September 1961, but receded quite considerably on at least three occasions. The first one was captured by the July 1972 photograph, when the vegetation line was 38.1 (±9.4) m landward of the December 2013 line, the second was observed in the July 1983 photograph, and the third in April 2002, when it receded approximately 15 m from its April 2001 position.

The southern end (WAR3) of this embayment did not experience much accretion at all. Only 10.8 (±3.7) m accreted since July 1972. Actually, the fastest progradation period occurred between July 1972 and November 1977, when the vegetation line accreted almost 13 m before experiencing recession the following years. A landwards displacement of the shoreline happened immediately after 1977, but was intensified after June 1981 and stopped by September 1984. The southern end experienced a slow recovery in the next 10 years and after February 1993, not much oscillation occurred, either seawards or landwards.

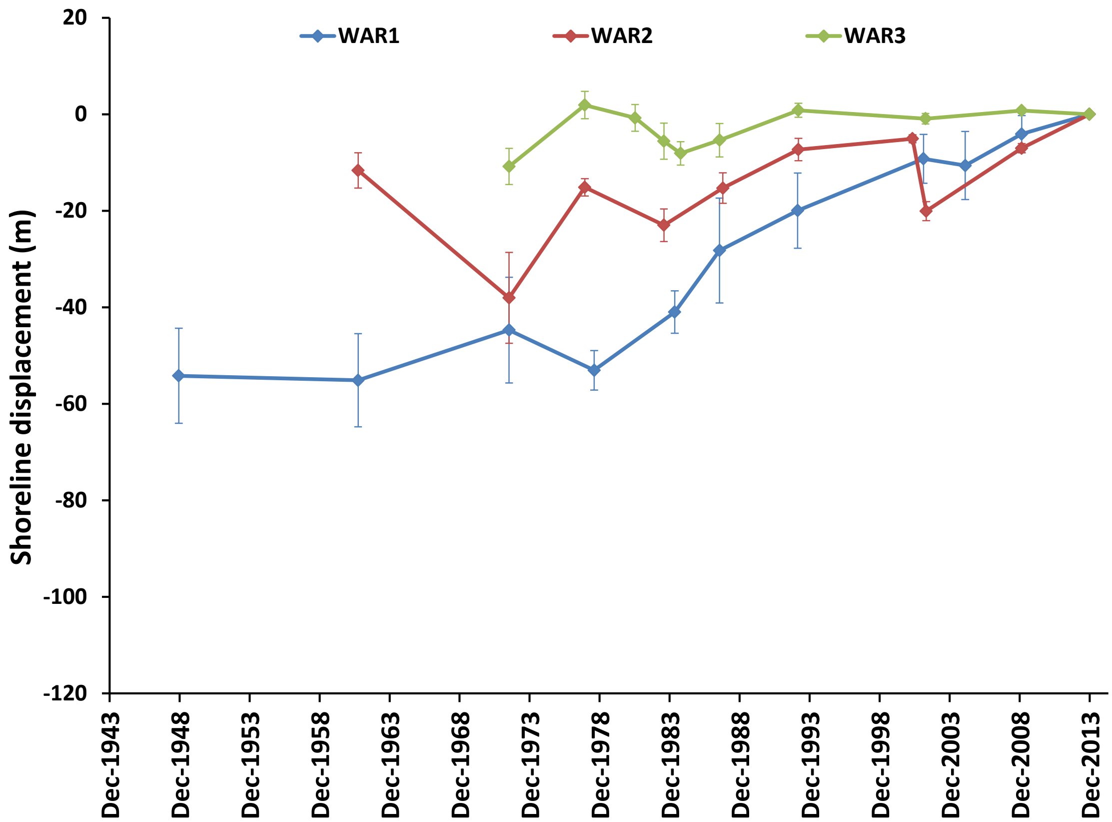

Figure 5.12 Warrain Beach mean shoreline displacement plotted with respect to its position in December 2013 based on historical aerial photographs. Vertical bars represent standard deviation based on 5 50-m spaced cross-sections along the beach. Location of profiles is shown in Figure 2.7.

In all three embayments (Seven Mile Beach-Comerong Island, Culburra and Warrain-Currarong) the shoreline displacement had a smaller spread at the southern end, followed by the middle and the northern ends, respectively. Although, at Seven Mile Beach-Comerong Island, the standard deviation was higher at SH2 (σ= 33.4) than at SH1 (σ= 23.1).

The beach behaviour at decadal time scale indicates positive displacement of the shoreline (beach accretion) not only within the three beaches but also between the individual monitored sites, with the northern sites accreting at a faster rate than the middle and southern end, in the last 40-65 years. This establishes a baseline for understanding how much sand has been deposited within each individual tertiary level compartment in the past decades.

Further insight into the dynamic nature of the beach and foredune can be gained from a comparison of the topography captured in LiDAR acquired in 2004 and 2011. The DEM difference between 2004 and 2011 LiDAR data shows areas in the barrier-beach system that have accreted or eroded in the seven-year span at Comerong Island (Figure 5.13), Culburra (Figure 5.14) and Warrain (Figure 5.15).

An assessment of vertical accuracy of the data needs to be made before making any geomorphic analyses, when considering Figures 5.13 to 5.15. Judging from the light red (0-0.5 m) erosion areas that predominate at the back of the foredune, it is inferred that one of the surveys is slightly offset in the vertical domain. The old inactive vegetated beach ridges at the back of the active foredune, could not have been eroded so uniformly over time, even for a few decimeters. This area should have accreted or remained at the same elevation over time. Therefore, either the 2004 survey shows slightly higher elevations or the 2011 survey shows lower elevations. This offset might have been related to differences in how the bare ground algorithm operated in the two datasets and vegetation might not have been removed in the same way.

Minor innacuracies apart, at Comerong Island (Figure 5.13), accretion was observed in the swash zone and at the berm (light to dark blue). It seems clear, as well, that both the foredune ridge and the some of the old ridges have eroded (dark red) over time. This loss of sand on the ridges can be expected due to the wind aceleration experienced in those areas.

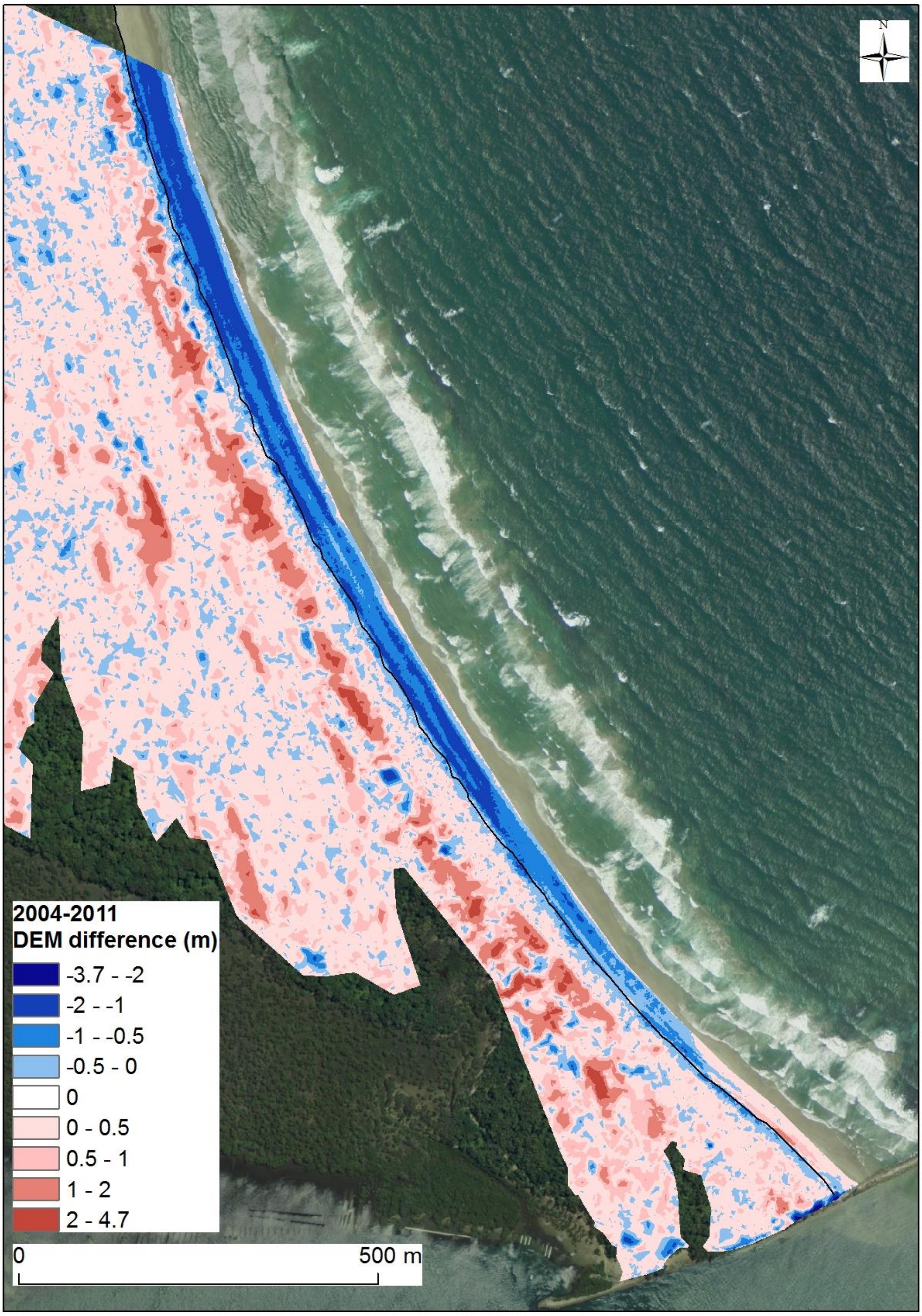

Figure 5.13 Elevation difference between DEMs based on LiDAR captured in 2004 and 2011 at Comerong Island. Red areas indicate erosion and blue areas indicate accretion over time. The black line represents the dense vegetation limit (vegetation line) in the berm digitised from the 2009 aerial photograph. Background imagery © NSW Government. Land and Property Information (LPI) 2013.

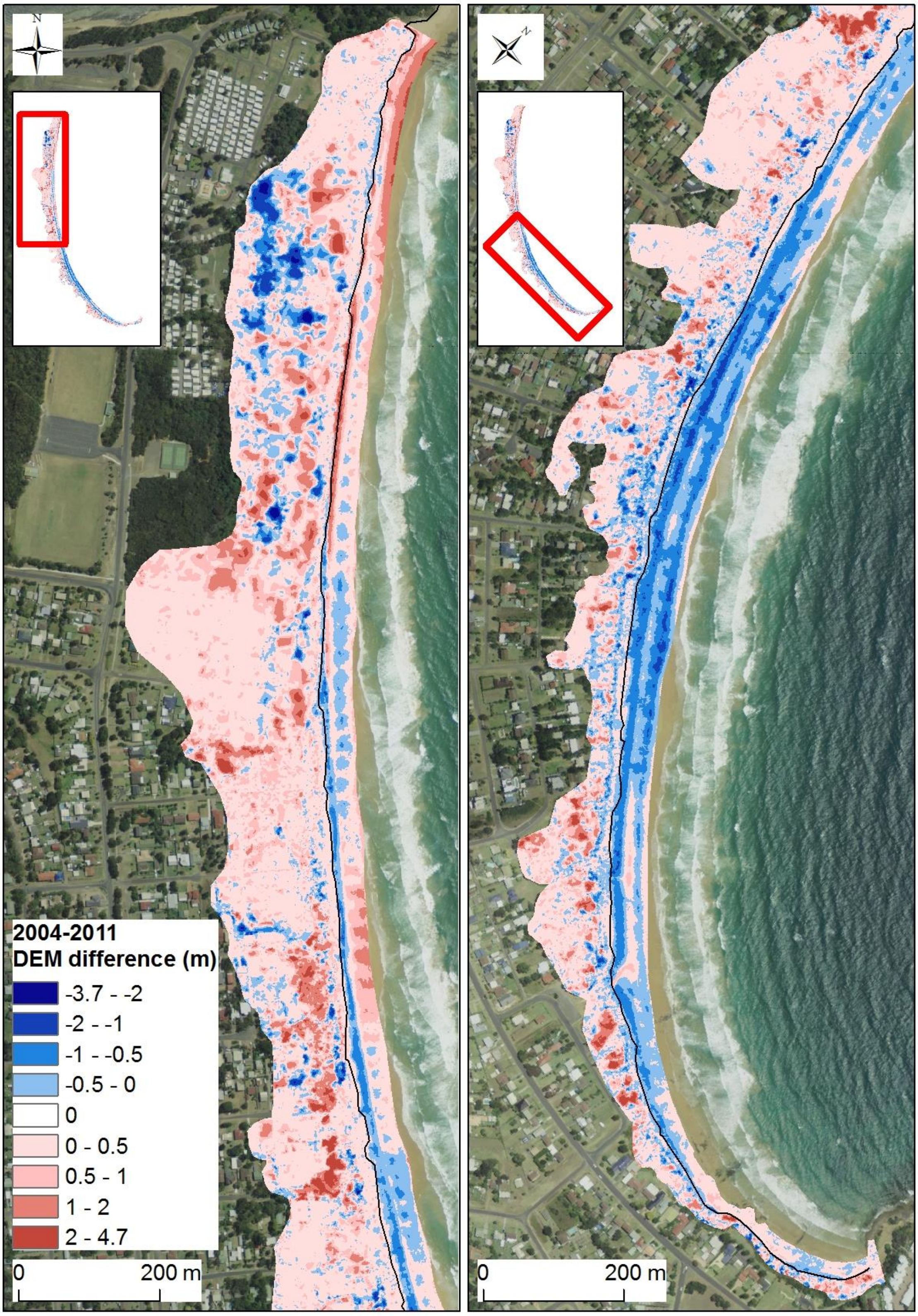

Figure 5.14 Elevation difference between DEMs based on LiDAR captured in 2004 and 2011 at Culburra. Red areas indicate erosion and blue areas indicate accretion over time. The black line represents the dense vegetation limit (vegetation line) in the berm digitised from the 2009 aerial photograph. Background imagery © NSW Government. Land and Property Information (LPI) 2013.

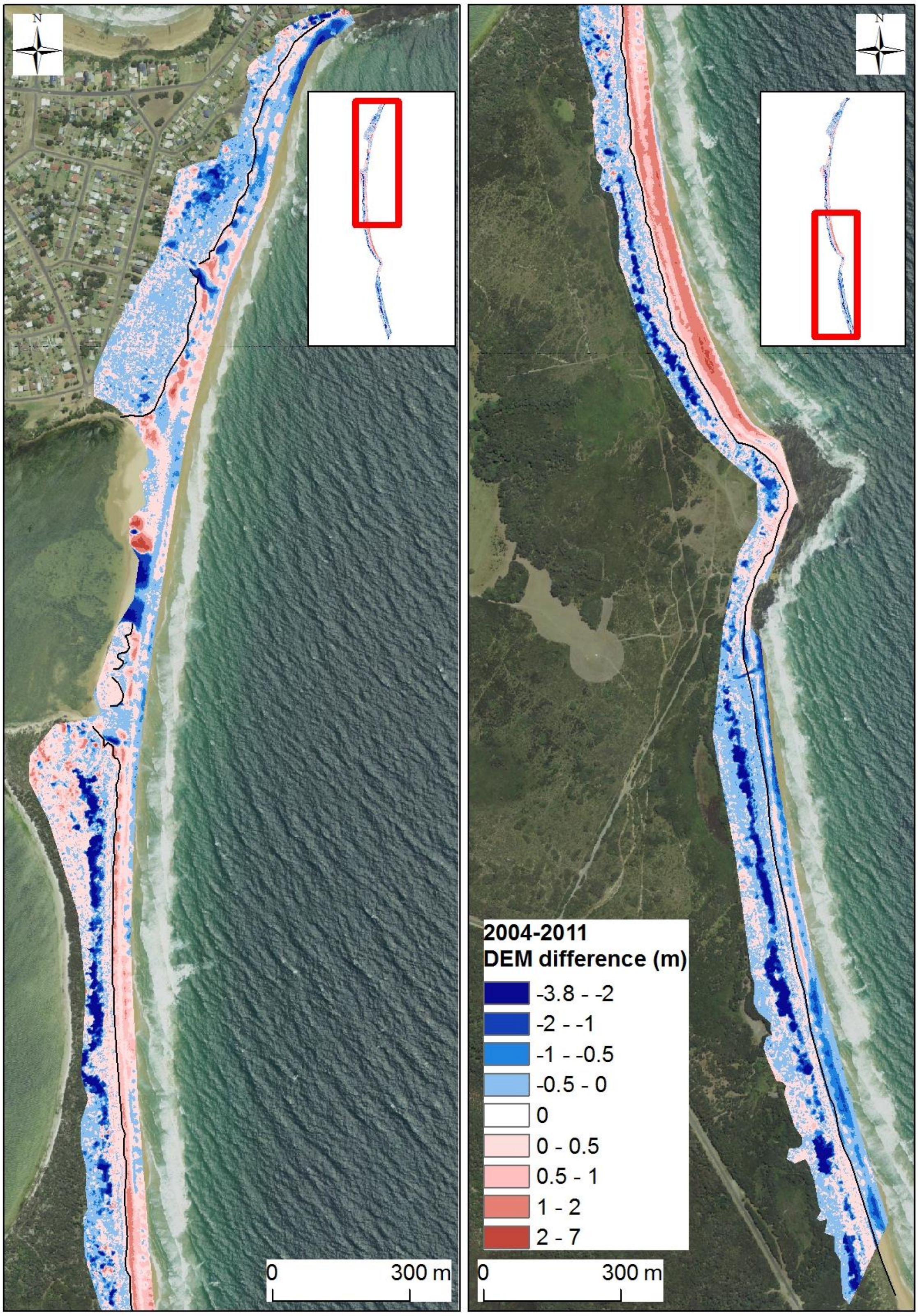

Figure 5.15 Elevation difference between DEMs based on LiDAR captured in 2004 and 2011 at Warrain. Red areas indicate erosion and blue areas indicate accretion over time. The black line represents the dense vegetation limit (vegetation line) in the berm digitised from the 2009 aerial photograph. Background imagery © NSW Government. Land and Property Information (LPI) 2013.

At Culburra (Figure 5.14), accretion was observed in the sparsely vegetated area of the berm (immediately seawards from the vegetation line) and in the swash zone over time in the south and middle part of the beach (approximately 75 %). At the northern end this pattern disappeared and erosion happened, probably due to a storm event that left a scarp adjacent to the vegetation line.

In general terms, erosion occurred on the lightly vegetated areas of the berm (seawards from the black line) and swash zone, northwards of Kinghorn Point, at Warrain (Figure 5.15). South of Kinghorn Point the opposite occurred. Throughout the area covered by Figure 5.15 (approximately 50 % of the Warrain-Currarong embayment), the foredune seems to have accreted considerably between 2004 and 2011.

5.6 Beach behaviour at short time scale

The monthly monitoring of the beach state started first at Seven Mile Beach-Comerong Island between 2011 and 2012 by the Water Research Laboratory (WRL) at University of New South Wales, and after a year gap, it was expanded as part of this project to Culburra Beach and Warrain-Currarong Beach between December/2013 and November/2015. Further details about these two periods can be found in the Appendices 7 and 8, whereas only a short summary of the monitoring findings will be presented in this section.

The envelopes of beach profile at Seven Mile Beach-Comerong Island are shown in Figure 5.16. The height of the incipient foredunes at SH1, SH2 and SH4 is approximately 4 m, whereas at SH3 it is 6.5 m. Between 2011 and 2015, the beach width (0 m AHD) fluctuated over 46 m at SH2, 40 m at SH3, 36 m at SH1, and 32 m at SH4. In terms of volume, SH3 experienced the greatest variability (76.6 m^3/m), followed by SH2 (66.3 m^3/m), SH4 (52.5 m^3/m) and SH1 (45 m^3/m). No consistent signs of beach rotation, determined by phase relation, between the northern (either SH1 or SH2) and the southern (SH4) profiles could be observed.

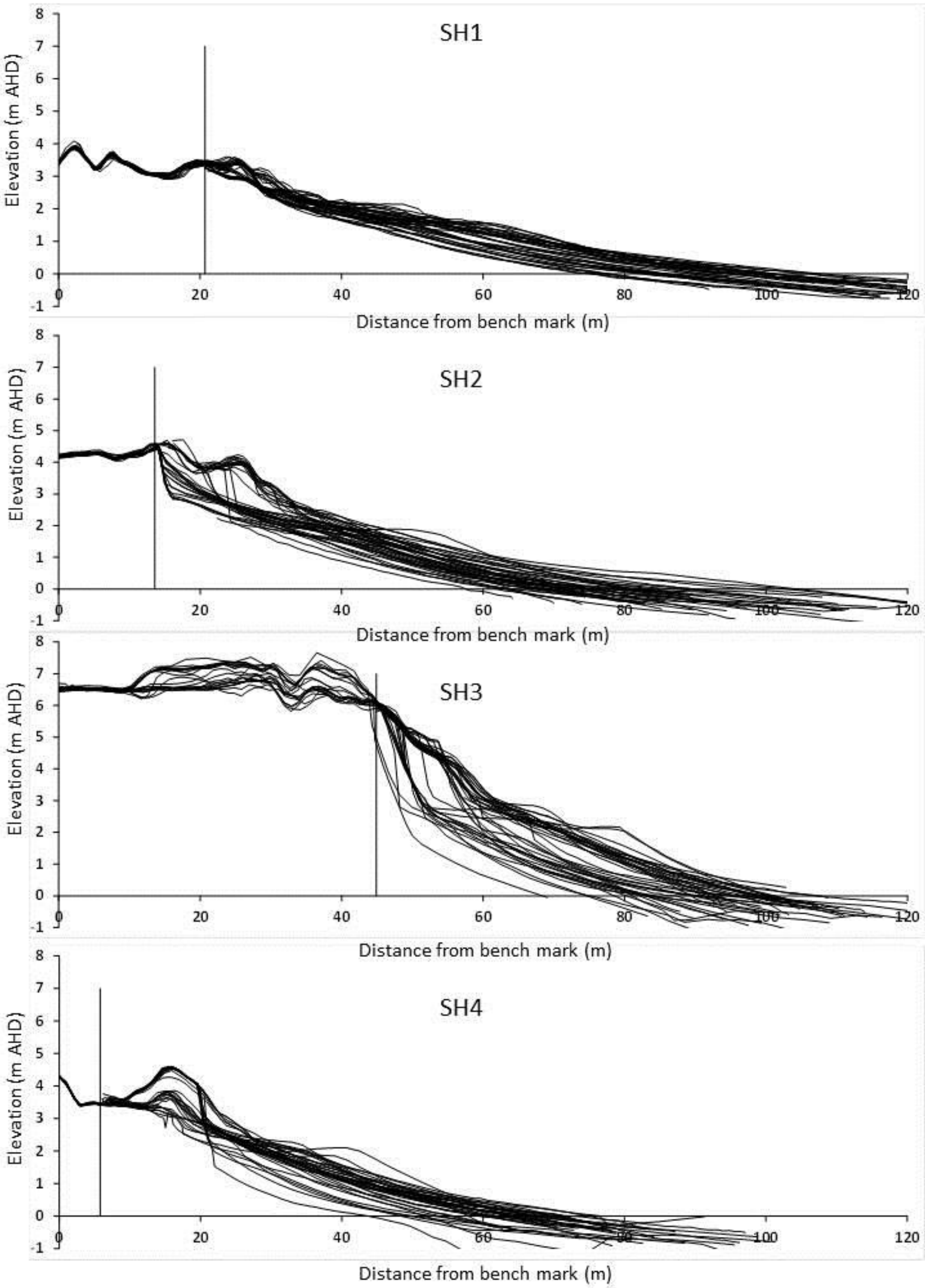

Figure 5.16 Seven Mile Beach-Comerong Island envelopes of profiles between 2011 and 2015. Vertical bars indicate the benchmarks used for volume and beach width calculation.

Figure 5.17 shows the beach envelopes at Culburra Beach. The height of the incipient foredune decreases towards the south, from 4.5 m at CUL1 to 3 m at CUL3.

Between 2013 and 2015, the width (0 m AHD) fluctuation of Culburra Beach decreased towards the north. The shoreline shifted 30 m at CUL3, 27 m at CUL2 and 24 m at CUL1. In terms of volume variability, there was not marked difference among the 3 profiles. CUL3 experienced a difference between the minimum and maximum volume of 54.5 m^3/m, followed by CUL1 (53.6 m^3/m) and CUL2 (51.8 m^3/m). Some signs of beach rotation, determined by phase relation, between the northern (CUL1) and the southern (CUL3) profiles, during the first eight months of 2014, the last months of 2015, as well as, during isolated months of March/2015 and June/2015 could be observed.

The envelopes of beach profiles at Warrain-Currarong Beach between 2013 and 2015 are shown in Figure 5.18. The height of the incipient foredunes decreased from 5.5 m at WAR1 to 4 m at WAR2. No incipient foredune was observed at WAR3. The beach width (0 m AHD) fluctuation decreased towards the south. The shoreline shifted 32 m at WAR1, 28 m at WAR2 and only 14 m at WAR1, whereas volume fluctuated by 71 m^3/m at WAR1, 64 m^3/m at WAR2 and 21 m^3/m at WAR3, during the monitoring period. The deviations of Warrain Beach width at each survey line from the mean indicates some beach rotation, determined by phase relation, between the northern (WAR1) and the southern (WAR3) profiles. A strong negative phase relation occurred between February and August/2014, and other isolated monitored months such as October/2014 and June/2015. While WAR1 accreted, WAR3 retreated and vice-versa.

The three beaches studied here have shown no synchronized behaviour in terms of linear trend in shoreline position, direction and magnitude of beach oscillation and rotation as identified for the NSW beaches of Narrabeen, Moruya and Pedro (Short et al., 2014), suggesting that embayed beaches along the coast may not necessarily behave in a similar manner. These findings need to be reassessed in the future when results from a longer monitoring period are available. Due to the short-term monitoring period, longer-term trends of beach behaviour, as well as the establishment of a link with wave climate and the Southern Oscillation Index (SOI), such as the one proposed by Ranasinghe et al. (2004), Short and Trembanis (2004) and Harley et al. (Harley et al., 2011), could not be addressed here. Nevertheless the envelope of profiles demonstrated variability in profile form for different sections of each individual beach that compose the secondary compartments. It also establishes the elevation of the foredune at different locations to improve volumetric calculations of sand deposited at each individual secondary compartment in the past decades.

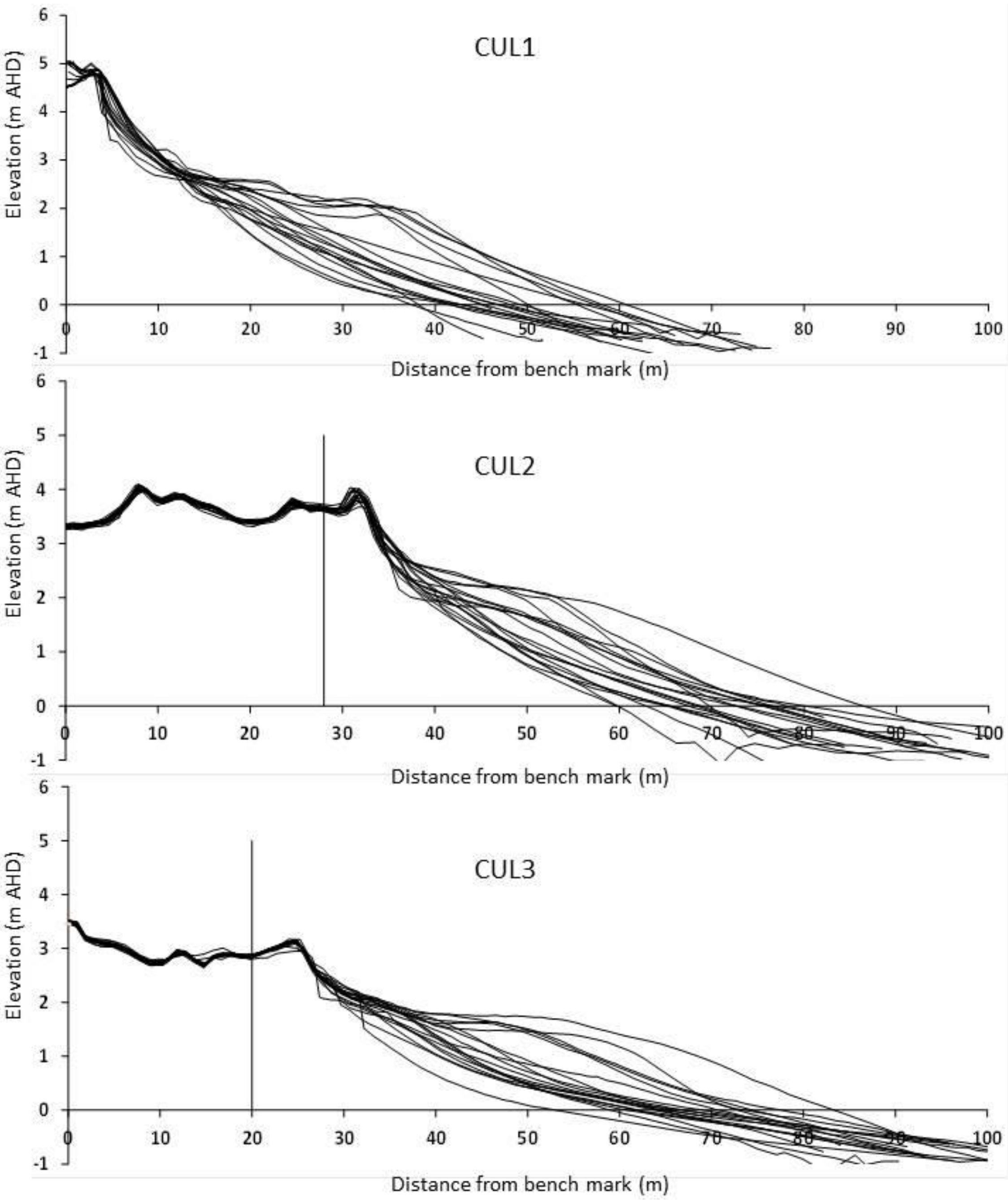

Figure 5.17 Culburra Beach envelopes of profiles between 2013 and 2015. Vertical bars indicate the benchmarks used for volume and beach width calculation.

Between January/2011 and December/2015, 17 major storms (wave power > 10 x 10^4 kW/m) impacted the coastline. Five of those storms happened before 2013 when only Seven Mile Beach-Comerong Island was being monitored by the WRL, whereas nine occurred after December/2013, when the monitoring resumed at Seven Mile

Beach-Comerong Island and was extended to Culburra and Warrain-Currarong beaches. Figure 5.19 depicts the wave data recorded at the Batemans Bay offshore wavebuoy (100 km to the south). Due to technical problems between July and October/2015, the last two major storms were not recorded by the Batemans Bay buoy. Data was extracted from the Sydney offshore wavebuoy (130 km to the north), for that period, to complete the series of major storms presented in Table 5.2.

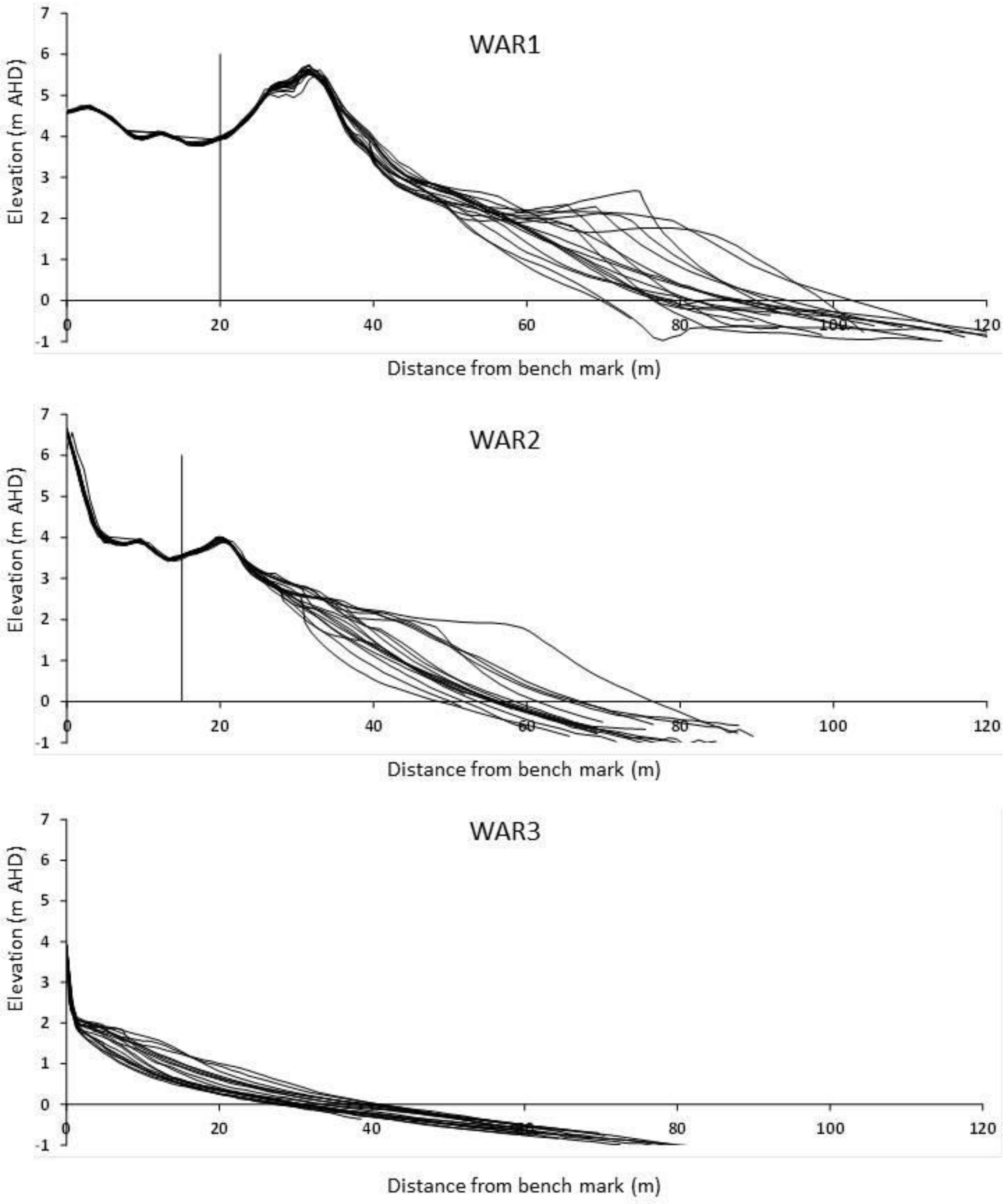

Figure 5.18 Warrain-Currarong Beach envelopes of profiles between 2013 and 2015. Vertical bars indicate the benchmarks used for volume and beach width calculation.

Table 5.2 Characteristics of storms whose wave power was higher than 10 x 10^4 kW/m. Hsig, T and Dir values from specific storms were extracted from the moment wave power peaked. Storm duration was calculated based on the number of hours whose Hsig remained higher than 3 m.

Date	Hsig (m)	T (s)	Dir (°)	Power ($\times 10^4$ kW/m)	Storm (Hsig > 3m) duration (hours)
22/07/2011	5.3	13.8	111	19.1	99
08/03/2012	5.1	11.4	142	14.6	34
06/06/2012	6	12.1	149	23.3	33
01/08/2012	4	14.8	134	11.8	26
12/10/2012	5	10.8	151	12.8	23
29/01/2013	4.2	12.1	142	10.7	31
25/06/2013	5.1	10.3	109	13.7	49
17/09/2013	6.3	10.3	82	19.7	14
12/04/2014	4.6	11.4	131	12.5	49
04/05/2014	4.6	14.8	152	15.8	30
19/07/2014	4.5	12.9	161	11.6	35
18/08/2014	5.4	10.8	144	15.6	49
09/04/2015	4.2	12.1	152	11.1	33
21/04/2015	5.3	11.4	149	15.1	20
14/05/2015	3.9	13.8	151	10.3	33
17/07/2015	4.6	10.3	189	10.5	43
30/08/2015	4	13.8	185	10.1	49

Wave refraction scenarios modelled using STWAVE for the mean wave climate and the 8 strongest storms of 2011-2013 listed in Table 5.2 are presented in Figure 5.20. Under average conditions (top left diagram) wave attenuation happens in the south and higher waves occur in the north of Seven Mile Beach-Comerong Island. The storm of July/2011 (5.3m/13.8s/111°) shows an amplification of wave heights towards Penguin Head and, therefore, higher waves around Culburra, as well as parts of Seven Mile Beach-Comerong Island. A southward decrease in wave heights arriving at the coastline can be seen in the modelled storm of March/2012 (5.1m/11.4s/142°), similar to what happened in the June/2012 (6m/12.1s/149°) storm, the most powerful during the 2011-2015 period. The storm of August/2012 (4m/14.8s/134°) resulted in wave heights of approximately 4 m in most of Seven Mile Beach-Comerong Island with slightly smaller waves around SH2. Longshore variation in wave heights, with 4 m waves approaching Gerroa and 2.8 m waves around Comerong Island occurred during the storm of October/2012 (5m/10.8s/151°).

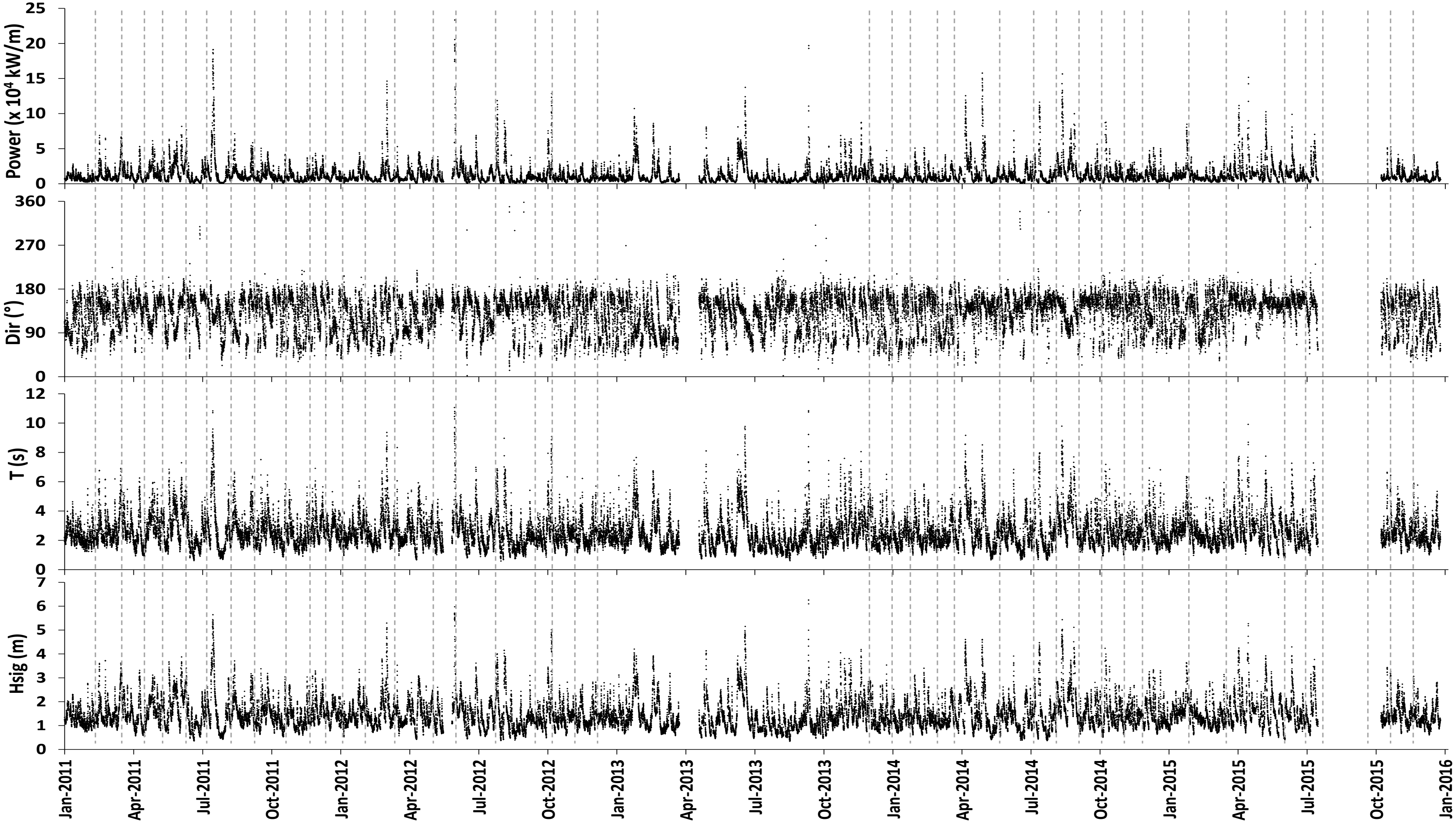

Figure 5.19 Offshore wave data recorded at Batemans Bay between 2011 and 2015. Vertical dashed lines represent beach surveys taken at Seven Mile Beach-Comerong Island, Culburra and Warrain-Currarong beaches.

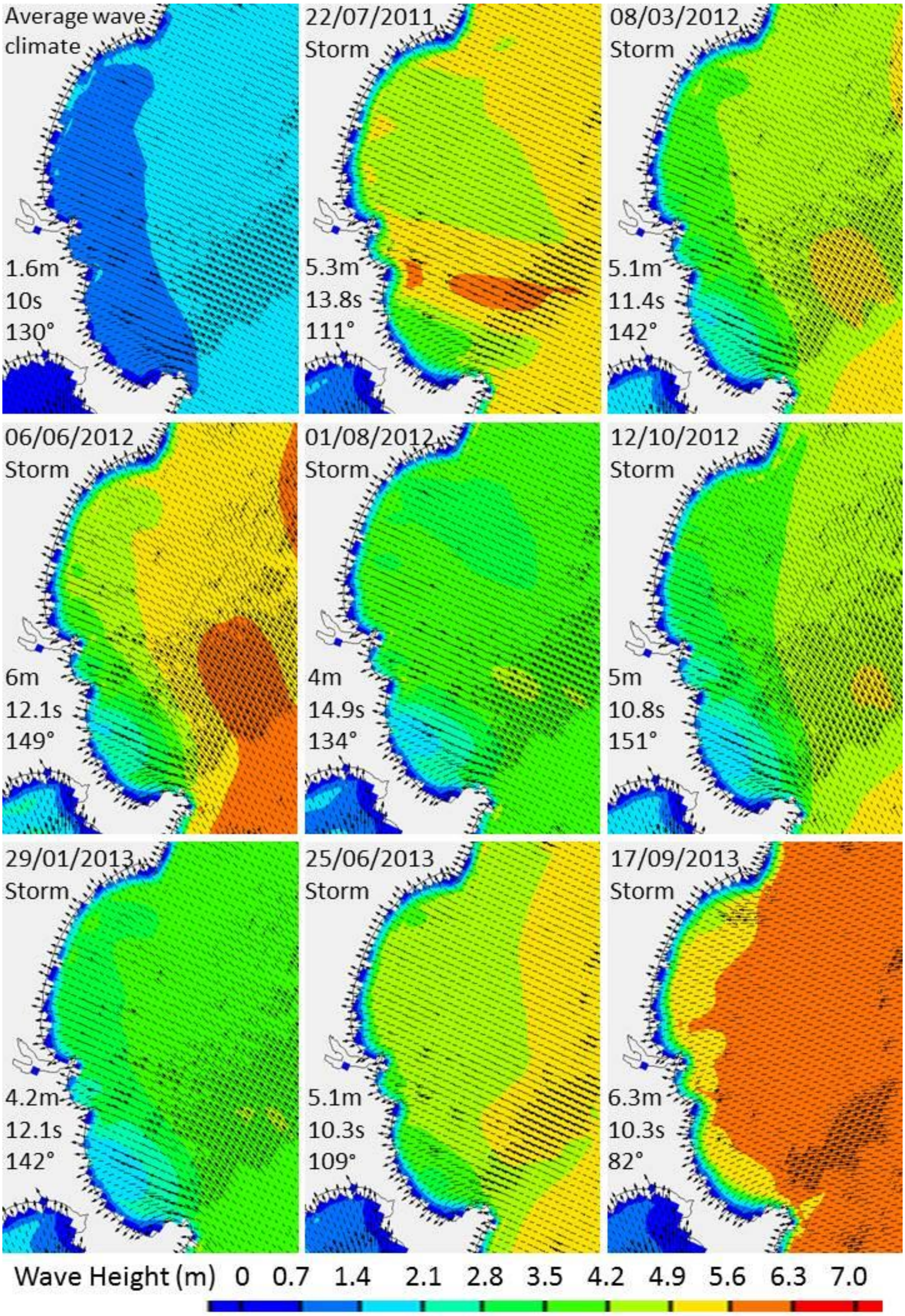

Figure 5.20 Wave refraction diagrams modelled using STWAVE for average wave condition (top left diagram) and the eight strongest storms of 2011, 2012 and 2013 listed in Table5.2. Arrows indicate wave direction, whereas colours represent wave height.

Unexpectedly, both the Jul/2011 and Mar/2012 storms, the third and seventh strongest storms of the entire period, respectively, left no trace of their effect in monitored profiles. In fact, SH2, SH3 and SH4 increased in volume immediately after the Jul/2011 storm. On the other hand, the Jun/2012 storm, the strongest storm in the 2011-2015 period, caused major erosion, especially on SH1, SH2 and SH3. These observations can be partially explained by the combination of an elevated water level during the June/2012 storm, when the highest tide reached 2.08 m (chart datum), approximately 0.7 m and 0.3 m higher than the tides in Jul/2011 and Mar/2012, respectively, enabling waves to extend further landwards.

During 2013, three major storms impacted the study area. A southwards decrease in wave heights arriving at the coastline occurred in the storm of January (4.2m/12.1s/142°), a similar pattern to what happened during the first two storms of 2012. Wave height contours parallel to the shoreline indicating little longshore variation along Seven Mile Beach-Comerong Island occurred during the second major storm (5.1m/10.3s/109°) of 2013, which had a similar direction to the 2011 storm. Likewise most of the southeasterly storms, the more protected Warrain-Currarong embayment experienced smaller waves than Seven Mile Beach-Comerong Island and Culburra Beach. The September/2013 storm (6.3m/10.3s/82°), was the second most powerful of the entire 2011-2015 period and the only major storm from the easterly direction. During this storm, higher waves propagated towards Comerong Island and Penguin Head, while, smaller waves occurred in the northern end of Seven Mile Beach-Comerong Island. This last storm of 2013 was probably responsible for the modifications that occurred at SH2 and SH3 and the formation of steep scarps observed when the monitoring resumed, as well as the scarp found when the monitoring started at CUL1 and CUL3.

Wave refraction scenarios for the 9 strongest storms of 2014-2015 listed in Table 5.2 are shown in Figure 5.21. In general terms, these storms were considered much weaker, and also came from a more southerly direction, than the ones that happened before 2014.

The storm of April/2014 (4.6m/11.4s/131°) produced higher waves in the northern half of Seven Mile Beach-Comerong Island than in the southern half of the embayment and at Culburra. At Warrain, the northern end received bigger waves than south of Kinghorn Point.

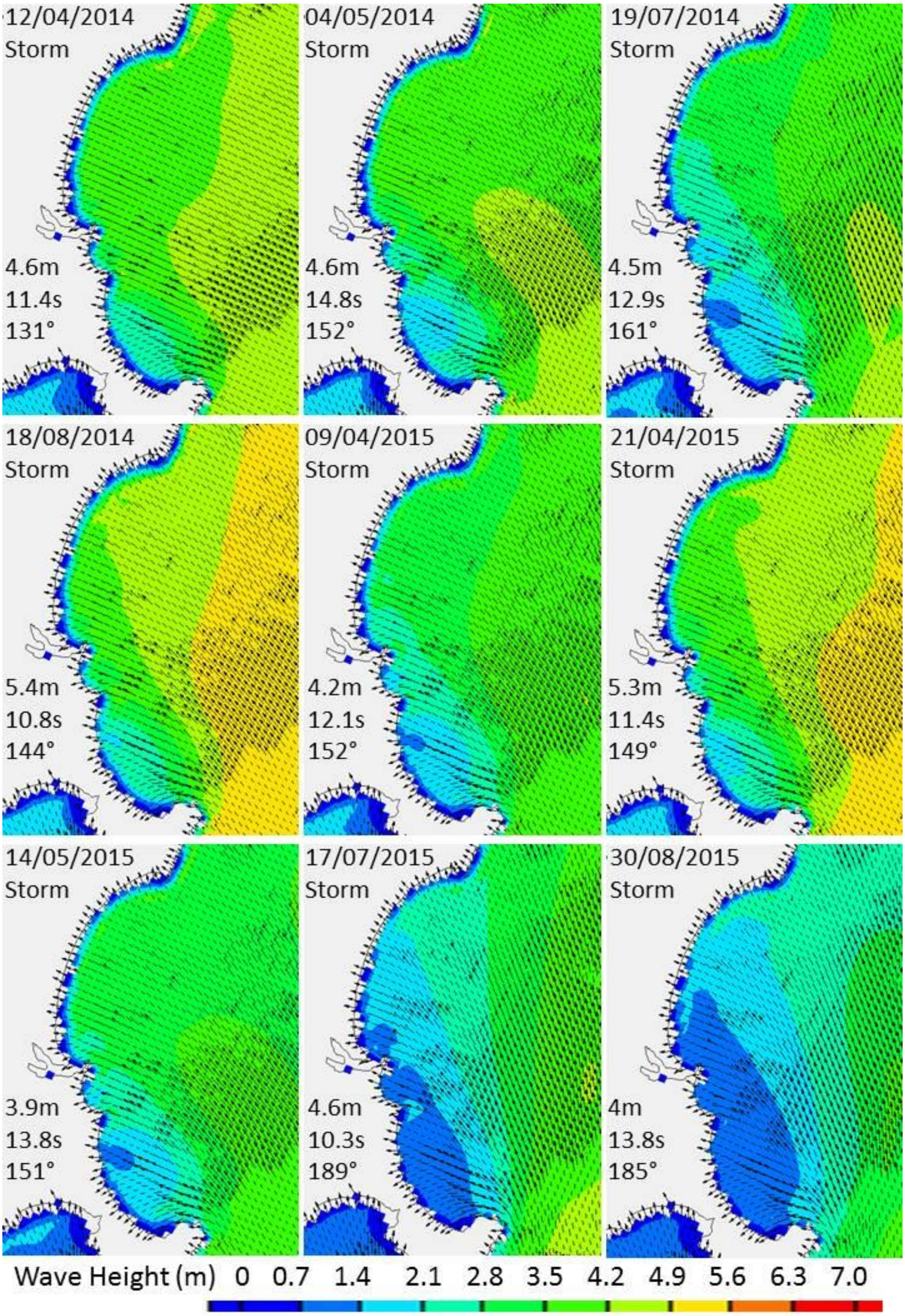

Figure 5.21 Wave refraction diagrams modelled using STWAVE for the strongest storms of 2014 and 2015 listed in Table 5.2. Arrows indicate wave direction, whereas colours represent wave height.

As storm direction started to shift more to the south, a southward decrease in wave heights reaching the coastline occurred. The storm of May/2014 (4.6m/14.8s/152°), the fourth strongest storm of the 2011-2015 period, propagated through the northern end of Seven Mile Beach-Comerong Island and, therefore, the highest waves were indicated betweeen SH1 and SH2. Wave propagation during this storm was almost identical to the pattern observed during storms from similar directions, such as the last two of 2014 and the first three storms of 2015.

The storm of May/2014, the fourth most powerful storm of the entire period, was responsible for the scarp recession observed at SH3, but conversely, no loss of sand or morphological erosion happened at SH1 and SH2. In fact both parts of the beach increased in volume, whereas SH4 lost a small volume. This storm did not produce major changes in the other profiles located in Culburra or Warrain-Currarong beaches.

The storm of August/2014 impacted all the profiles on the three secondary compartments. At Seven Mile Beach-Comerong Island, a 2.3 m scarp and considerable volume loss was observed at SH4, whereas losses were reduced in the other three profiles to the north. At Culburra, a scarp was left at CUL3 with considerable loss of sand also at CUL2. At Warrain-Currarong, this storm impacted WAR2 more than the other profiles. It reduced considerably the volume in the swash zone and left a small scarp on the beach. Despite the impact of this storm on the three embayments, the tidal peak during this storm reached 1.5 m, approximately 0.1 m lower than the tidal peak during the May/2014 storm. It appears that the longer duration and the higher waves experienced during this storm played a more significant role than the power and tidal level associated with the May/2014 storm.

The tide peaked at 1.89 m (chart datum) during the storm of 21/04/2015, the highest level associated with any storm in 2014-2015. It impacted mainly SH1, SH2, CUL2 and WAR1. Despite the high tidal level and high waves registered during this storm, it appears that its short duration limited the erosive effects associated with it.

The highest waves of the southerly storms of July (4.6m/10.3s/189°) and August/2015 (4m/13.8s/185°) missed the study area and propagated further north. Waves refracted at Beecroft Peninsula and also at the underwater rock reef known as Sir John Young Banks, resulted in decreasing wave heights around Comerong Island, Culburra and Warrain-Currarong beaches, whereas higher waves reached Gerroa at the northern end of Seven Mile Beach-Comerong Island. The impact of July/2015 storm was not apparent at the profiles apart from the minor erosion caused at SH3 and SH4. It appears that despite the 43h duration of waves exceeding 3 m, the level during the peak of the tide was less than 1.6 m (chart datum), reducing its erosive potential considerably. The storm of August/2015 was felt drastically, with substantial volume erosion detected at SH3 and possibly at SH4 too, and considerable erosion at CUL2, CUL3, WAR1 and WAR2. During the August/2015 storm, tide peaked at 1.67 m (chart datum) and waves exceeded 3 m for four more hours than the previous storm.

It was apparent that a northward longshore sediment transport occurs at the southern end of Seven Mile Beach-Comerong Island and Culburra Beach due to the more oblique wave incidence caused by the southerly storms of 2015. Although, the more sheltered area of Currarong at WAR3 is an exception to this process.

5.7 Breaching dynamics at Shoalhaven Heads

The dynamics of sand transport during breaching events at Shoalhaven Heads can be better understood by looking at monthly surveys of RTK-GPS elevation data, collected by Shoalhaven City Council, before and after flood events (Figure 5.22), such as the one that happened at the end of June/2013.

In early 2011, LiDAR data processed for bare ground elevation showed a stretch of approximately 300 m of beach formed connecting Seven Mile Beach and Comerong Island, after at least 11 years since the last brief opening that occurred in 1999/2000. The remains of the foredune could be identified by the scattered deposits of sand in the north and south, reaching 5 m in elevation (AHD), and a berm crest of 2.2 m high was formed. RTK-GPS data collected in June 2013 showed a slight increase in the berm crest height to 2.5 m and the deposition of sediments behind the berm.

During the passage of the East Coast Low at the end of June/2013, Shoalhaven City Council bulldozed Shoalhaven Heads, through the dry notch, allowing fresh water discharge into the ocean. This process resulted in the scouring of the beach transporting sand offshore and the formation of a 140 m wide channel 3.5 m deep, as can be observed in the July/2013 image (Figures 5.22 and 5.23). The following months show the gradual closing of the channel and the return of most of the lost sand by April/2014, when the beach was reformed across the entrance.

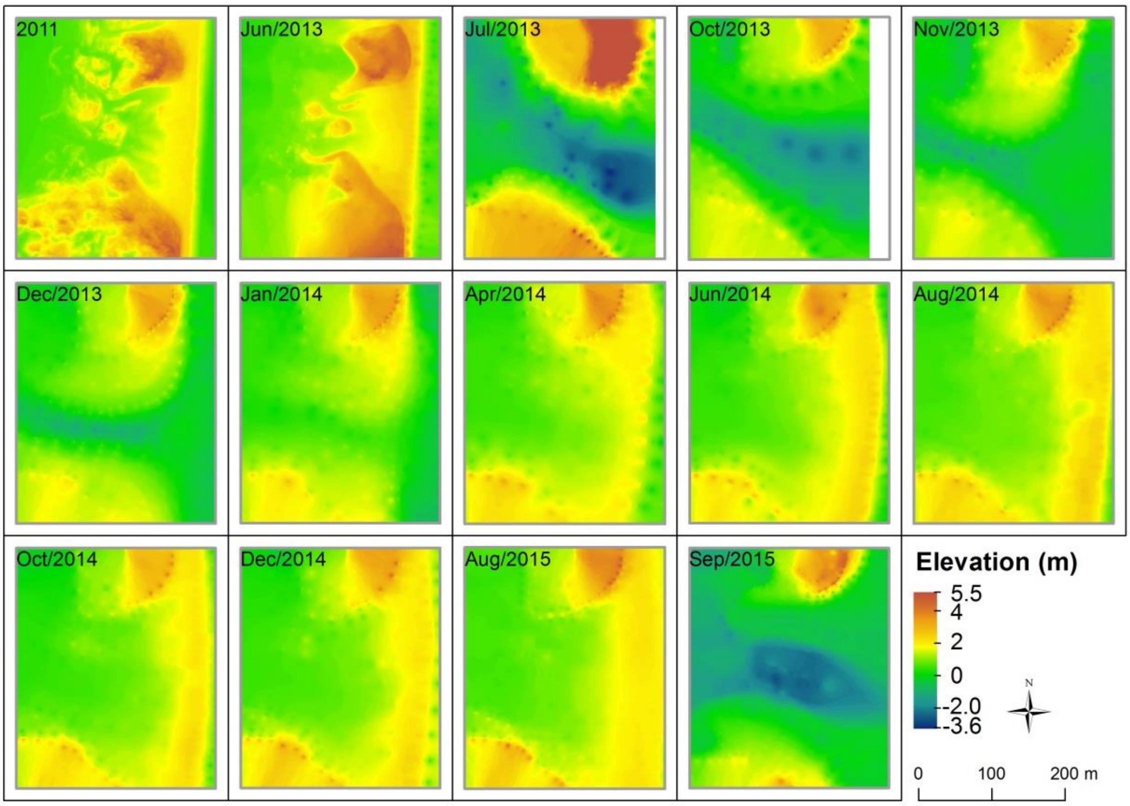

Figure 5.22 Shoalhaven Heads dynamics before and after the mechanical opening by Shoalhaven City Council to mitigate the floods during the 2013 and 2015 East Coast Lows. Map sequence shows the gradual closing of the channel after the breaching event that happened in July/2013, and the reopening after the complete closing of the estuary in September/2015. Elevation data (m AHD) collected using a RTK-GPS, except 2011 map derived from LiDAR.

From April/2014 to August/2015 the beach accreted both in width and height, prograding seawards, and in the following month, another East Coast Low event, forced the Shoalhaven City Council to mechanically open up Shoalhaven Heads one more time.

Figure 5.23 Panoramic photograph taken at Shoalhaven Heads, with Comerong Island in the background, on 18/07/2013, weeks after the mechanical opening of the estuary. The beach deposit was eroded offshore by the floods of June 2013 and a 140 m wide channel was formed facilitating the temporarily exchange of sediments from the estuary to the nearshore.

The 2013 breaching event has resulted in a loss of approximately 200,000 m^3 of sand as the volume decreased from 485,000 m^3 in June/2013 to 284,000 m^3 in July/2013 (Figure 5.24) in the sand volume above -3.65 m AHD. A loss of approximately 165,000 m^3 happened during the 2015 event, when the total volume decreased from 459,000 m^3 in August/2015 to 294,000 m^3 in September/2015.

The breaching dynamics at Shoalhaven Heads demonstrates not only the volumes exchanged between the beach-berm and the shoreface, but also how fast the recovery from an event of the magnitude of the 2013 storm occurs.

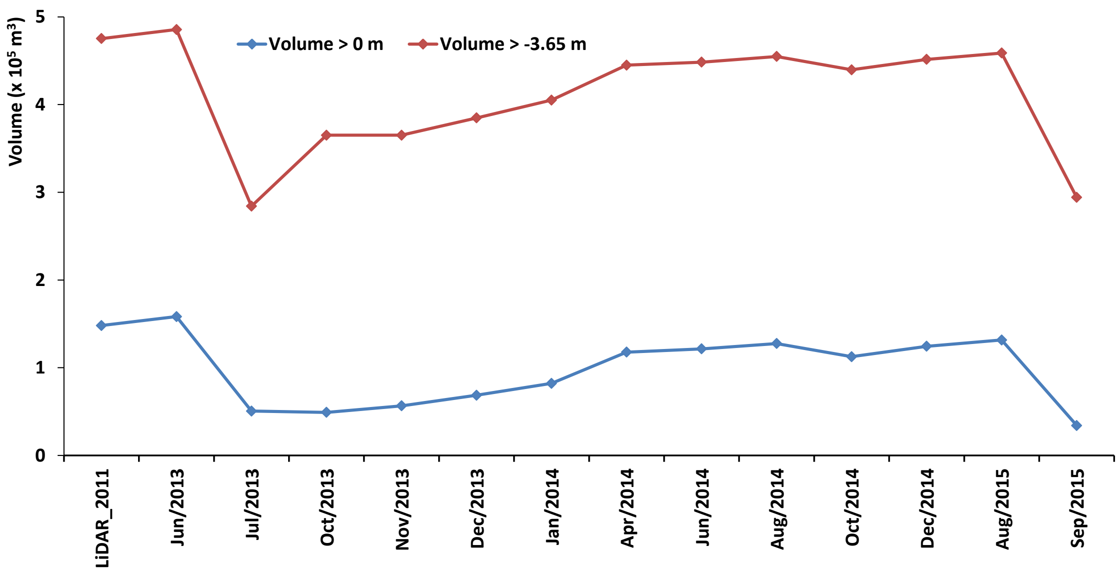

Figure 5.24 Volume change above 0 m (blue) and -3.65 m (red) for Shoalhaven Heads based on LiDAR and RTK-GPS elevation (AHD) collected between 2011 and 2015, for the area represented in Figure 5.22. The breaching events of 2013 and 2015 resulted in a temporary loss of approximately 200,000 m^3 and 165,000 m^3 of sediment above -3.65 m of elevation, respectively, from the beach-berm to the shoreface.

5.8 Summary

The Shoalhaven coastal compartment is composed of three tertiary level compartments: Seven Mile Beach-Comerong Island, Culburra and Warrain-Currarong, backed by prograded (approximately 88,000,000 m^3 above 0 m AHD), receded (4,650,000 m^3) and stationary (9,580,000 m^3) barriers, respectively. The beaches, the most active part of the barriers, showed marked longshore variation in the mean grain size ranging from 1 phi to 2.4 phi. Sediments get finer and sorted towards both ends of Seven Mile Beach-Comerong Island, and coarser and sorted towards the northern ends of Culburra and Warrain-Currarong beaches. Based on the mineralogy of the sediments, colour and morphometry of quartz grains, three very different sediment types can be assigned for the Shoalhaven coastal compartment. The first one encompasses the feldspar-rich, low carbonate, brown-coloured, more angular and less rounded sediments of Seven Mile Beach-Comerong Island, the second group is composed of carbonate-rich, orange-colour, more rounded and spherical grains of Culburra and north/middle Warrain beaches, and the third one is composed of carbonate-rich, brown-colour, more angular with varying degrees of sphericity grains near Currarong. The contrast in texture, shape and mineralogy of sediments indicate that the budget of the Seven Mile Beach-Comerong Island tertiary level compartment is independent of Culburra Beach and there is a possible significant source of sediments to Currarong Beach, despite the small size of the Currarong Creek catchment.

The beach behaviour at decadal time scale inferred by the changes in the vegetation line indicates positive displacement of the shoreline (beach accretion) not only within the three beaches but also at each individual monitored site, with the northern sites accreting at a faster rate than the middle and southern ends, in the past 40-65 years. At short time scale, the beach monitoring using RTK-GPS, showed a trend of erosion in the northern end and deposition in the south of Seven Mile Beach-Comerong Island between 2011 and 2012. However, between 2013 and 2015, a trend of accretion was only observed in the second northernmost profile (SH2) at Seven Mile Beach-Comerong Island, the northern end of Culburra and on all profiles at Warrain-Currarong. No consistent signs of beach rotation could be observed for Seven Mile Beach-Comerong Island, whereas some negative phase relation could be observed between the northern and southern ends of Culburra and Warrain-Currarong especially before September/2014. In general terms, the envelope of profiles demonstrated the variability in profile form for different sections of each individual beach that compose the secondary compartments. It also establishes the elevation of the foredune at different locations, that, associated with the shoreline displacement at decadal scale, forms the baseline to calculate the volumetric deposition of sand in each individual secondary compartment over the past decades.

During recent breaching events at Shoalhaven Heads in 2013 and 2015, a loss of approximately 165,000-200,000 m^3 of beach-berm sand to the nearshore occurred.

However, return of most of the lost sand in 2013 and rebuilding of the berm occurred within nine months after the triggering event.

Chapter 6: Offshore system

This chapter contains the results and discussion of data analyses for the offshore system, which includes the nearshore and shoreface of the Shoalhaven coastal compartment. A short introduction to the topic is provided first. Subsequent sections provide information about the texture, shape and mineralogy of the nearshore sediments, bathymetric changes at the nearshore associated with the fluvial contribution, shoreface sand availability and supply, and headland bypassing. Then, a final section summarises the findings in terms of sediment transport and processes.

These sections were designed to investigate the physical characteristics of the nearshore/shoreface, the volume of fluvio-estuarine sediments added to the nearshore off Shoalhaven Heads, the sediment availability within each individual tertiary level compartment to support a supply of shoreface sands to the beach, the possibilities of sediment exchange between the tertiary level compartments, and also between the Shoalhaven coastal compartment and the adjacent secondary level compartments to the north (downdrift loss) and to the south (updrift supply).

6.1 Introduction

The wave-dominated and embayed coast of southern NSW is characterised by sandy infilled embayments, partially filled with sand, separated by numerous rocky cliffed headlands that in some cases extend to the inner shelf, obstructing along-shelf transport (Wright, 1995). The coast is oriented NNE-SSW and is subjected to a generally moderate south to southeasterly wave climate; it is periodically affected by large coastal storms generated from a range of synoptic weather systems (Shand et al., 2011). Littoral drift is oriented from south to north, due to the oblique coastal orientation in respect to the dominant swell direction, whereas the East Australian Current consists of a coastal southward flow and a series of large warm and cold eddies (Ridgway and Dunn, 2003), with relatively low bottom currents over the shelf south of Sydney (Godfrey et al., 1980). Tides are semidiurnal with a spring range of 1.3 m (Short and Woodroffe, 2009) with significant diurnal inequalities (Wright, 1970).

The eastern Australian continental margin evolved by seafloor spreading between 82 and 60 million years BP (Hayes and Ringis, 1973, Weissel and Hayes,

1977) and rifting of the continental shelf, resulting in a relatively narrow and steep continental shelf less than 26 km in width and shelf break around 140 m depth in southern NSW (Davies, 1979). The inner shelf extends from the concave-up nearshore profile to depths of 50-60 m, and is composed of well-rounded, well-sorted, medium to fine quartose sands, with variable quantities of calcareous debris (Shirley, 1964, Davies, 1979). The much flatter mid shelf extends to depths of 100-120 m and sediments are composed of a mixture of mud and fine to very fine calcareous sand (Roy and Stephens, 1980), whereas the the outer shelf is composed of very coarse calcareous bioclastic debris (Wright, 1995).

Adjacent to Shoalhaven Heads, the nearshore has a very low gradient (0.3°) formed by the seaward part of the prograded barrier, a 15-22 m thick sand unit beneath the beach that thins seawards until a depth of 25 m. During flood events significant quantities of sediment load is debouched from Shoalhaven Heads into the nearshore, with gradual and partial shoreward return of the sand deposit constricting the outlet and re-establishing the beach across the entrance (see section 5.7). Beneath this shoreface accretion wedge, a layered sequence, at least 10 m thick, extents to depths of 30 m. This unit is composed of planar, gently landward-dipping beds, and possibly represents an estuarine/backbarrier muddy sequence. Seawards of the shoreface accretion wedge, a horizontally-bedded surficial sediment blanket less than 10 m thick covers the seabed and beneath this sequence, as well as the layered sequence, chaotic bedding of a channelled sequence occurs, suggesting fluvial channelling by the meandering Shoalhaven River system during lower sea-levels (Roy and Ferland, 1987).

Off Culburra, the shoreface accretion wedge is poorly developed or absent, and the inner shelf is characterised by numerous rock reefs with pockets of sediment within the topographic lows that are generally less than 10 m thick. Off the Warrain-Currarong embayment, moderately to well-sorted, fine to medium sands, with 5-15 % of shell and different proportion of mud content were found in depths down to 25 m (Roy and Ferland, 1987, Ferland, 1987, Ferland, 1990). Further offshore, a 12 km-long submarine bedrock outcrop, known as Sir John Young Banks, extends between 35 and 105 m depth (Ferland, 1990). South of this bank and off Jervis Bay, there is a continuous convex-up shelf sand body extending 33 km along the southwest-northeast direction, that is 2 km wide and up to 25 m thick off the Beecroft promontory. The upper surface of this shelf sand body sits in water depths of approximately 50 m (Roy and Ferland, 1987).

6.2 Nearshore sediments

A total of 52 nearshore samples were collected specifically for this project off Seven Mile Beach-Comerong Island, Culburra and Warrain-Currarong Beaches, and Gerringong, the latter outside of the Shoalhaven coastal compartment. Due to the presence of consolidated rocky substrate, some nearshore samples could not be recovered.

Grain size analysis showed that the mean nearshore sediment size ranged from very coarse to very fine sand (-0.6 phi to 3.2 phi) (Figure 6.1). Nearshore grain size was more homogeneous at Seven Mile Beach-Comerong Island (mean = 2.4 phi and σ= 0.2 phi) and Culburra (mean = 2.3 phi and σ= 0.3 phi) than at Warrain-Currarong (mean = 1.9 phi and σ= 0.6 phi). At Seven Mile Beach-Comerong Island, the samples located in shallow water were finer towards both northern and southern ends, showing a similar pattern to the beach samples (see section 5.2). Finer sand was observed adjacent to Comerong Island and around the 20 m depth in the middle of the embayment, whereas coarser sands were found close to a rock reef near Gerroa and near the river entrance at Crookhaven Heads. The two shallow samples located at both ends of Culburra were composed of medium sand. Fine sands occurred in the other three samples within this embayment, with approximately 10 % mud content in the deeper samples. At Warrain-Currarong, sands located in shallow water are coarser towards the south and north of the secondary compartment. Two offshore samples adjacent to Kinghorn Point were composed of very fine sand with mud content of 24 %. The three samples collected off Gerringong, and therefore, to the north of Shoalhaven coastal compartment, were composed of fine (mean = 2.1 phi and 2.2 phi) and medium (mean = 1.4 phi) sand.

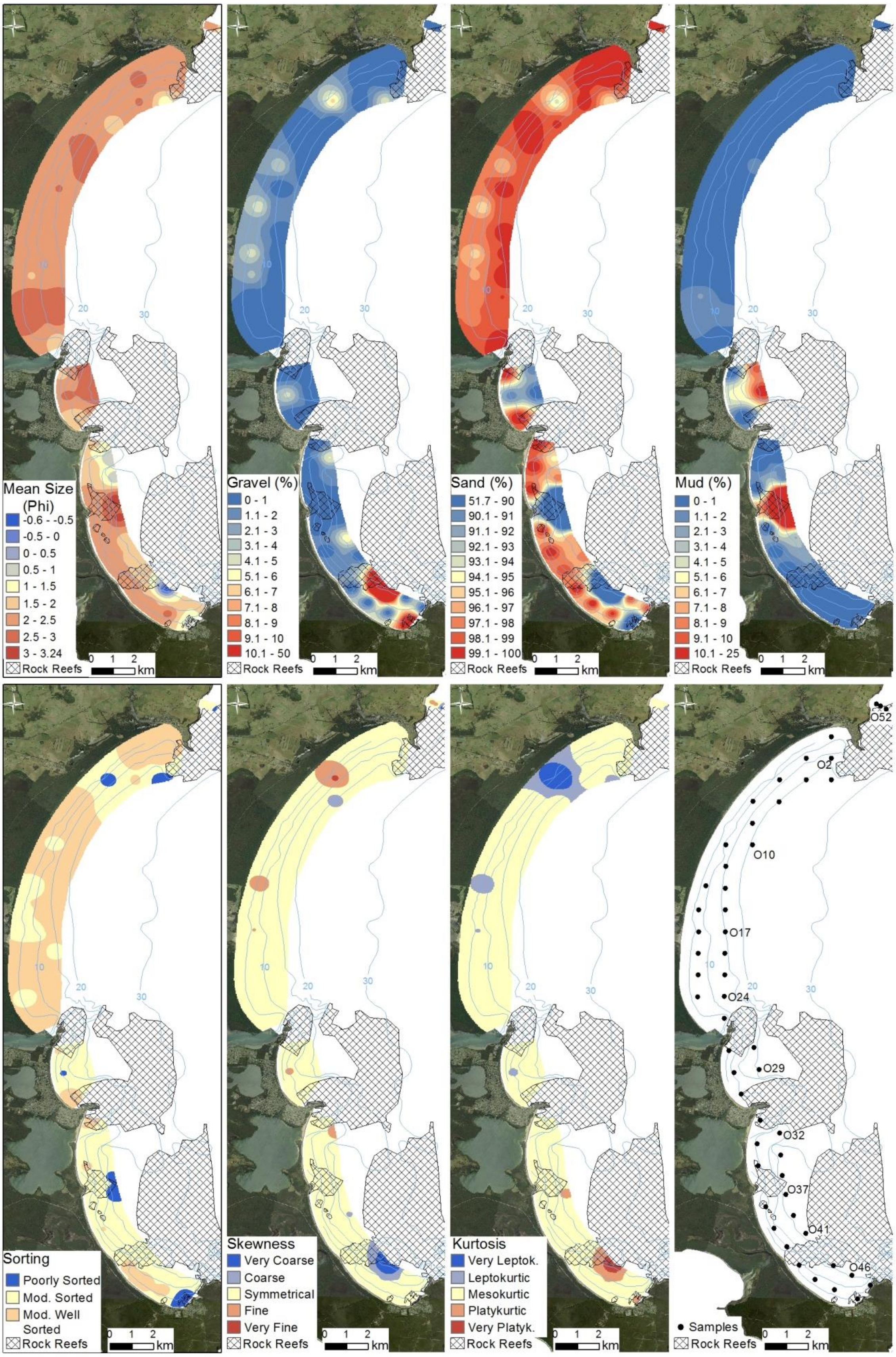

Figure 6.1 Mean grain size, percentage of gravel, sand and mud content, sorting, skewness and kurtosis of the nearshore samples. Samples selected for further sediment analyses are labelled. Background imagery © NSW Government. Land and Property Information (LPI) 2013.

Most of the nearshore samples from the Shoalhaven coastal compartment were moderately well sorted (n=25) or moderately sorted (n=18). However, poorly sorted samples also occurred (n=6), mostly associated with nearby rock outcrops. Moderately sorted (0.7-1 phi) sediments were predominant off Warrain and Culburra, whereas moderately well sorted (0.5-0.7 phi) sands were found between Crookhaven Heads and Gerroa. No trend in longshore sorting was observed for nearshore samples. In general, the deep samples are less sorted at Culburra and Warrain-Currarong than at Seven Mile Beach-Comerong Island.

Samples were mostly symmetrical with only one very coarse skewed sample located off Hammerhead Point, one very fine skewed sample located in the nearshore on the north of Seven Mile Beach, and a few coarse and fine skewed samples scattered across the area. In terms of kurtosis, most of the area is similar to a normally distributed curve (mesokurtic). Kurtosis was high (very leptokurtic) in a sample located in the nearshore on the north of Seven Mile Beach and low (very platykurtic) in a sample located seaward of Hammerhead Point.

Non-normal values of skewness and kurtosis indicate a mixing of two or more modal fractions (Folk and Ward, 1957). In the case of the very coarse skewed, very platykurtic sample located off Hammerhead Point, this might be associated with the presence of the rock reef nearby. On the other hand, no explanation could be attributed to the very fine skewed, very leptokurtic sample located in the nearshore on the north of Seven Mile Beach. The deepest sample (O52) collected towards Gerringong, was poorly sorted, very fine skewed and leptokurtic, differing significantly from the shallower samples that were moderately sorted, coarse skewed and mesokurtic. A close look at the O52 sample shows that it is composed of orange-colour sediments quite different from the brown-colour sands observed off Seven Mile Beach-Comerong Island. However, the fine fraction present in the sample seems similar to the fine fraction in samples of Seven Mile Beach near Gerroa, suggesting that some leakage of sediment may occur sporadically from the Shoalhaven coastal compartment towards Gerringong.

When compared to the offshore samples collected by Johnson (1974), a similar pattern of mean grain size predominates across the nearshore. However, a slight difference in results were observed off Culburra and Warrain-Currarong, mainly attributed to the sparse sampling in the area (Figure 6.2).

In a much wider area, extending to the middle shelf, Johnson (1974) found a quite complex spatial variation in median grain size with six contrasted areas. Two well defined bodies of medium sand (one on the northern half of the Shoalhaven Bight and the other one covering the Sir John Young Banks) separated from the other four areas: i) scattered pockets of coarse sand (<1 phi) associated with underwater extensions of onshore rock outcrop at Gerroa, Crookhaven Heads, Penguin Point and Sir John Young Banks; and belts of fine sand (> 2 phi) located ii) at the immediate offshore zone down to approximately 23 m contour seaward off Seven Mile Beach-Comerong Island; iii) at an almost isolated pocket of fine sand (> 2 phi) seaward of Warrain Beach; and iv) below the depth of 55 m particularly well developed approximately 8 km seaward off Gerringong.

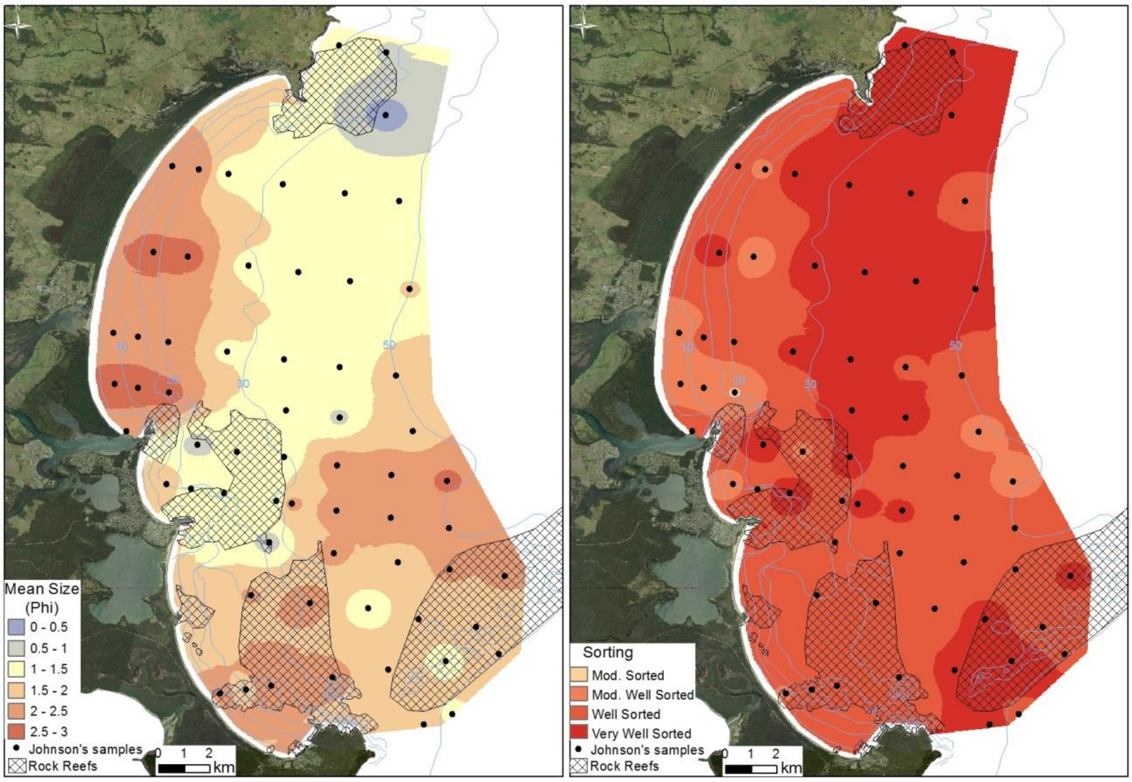

Figure 6.2 Interpolated map of Johnson's (1974) inner shelf sediments. Background imagery © NSW Government. Land and Property Information (LPI) 2013.

Comparing the results in shallower than 30 m depth, the similarity of values is clear at Seven Mile Beach-Comerong Island and in the area between Hammerhead Point and Currarong, where fine sands (2-3 phi) predominate. Johnson's (1974) findings are slightly coarser towards mid-north Warrain, Culburra and north of Seven

Mile Beach and no signs of very fine sand with high mud content were found adjacent to Kinghorn Point, possibly due to the lack of samples in these areas, influencing the interpolation results. Sorting, on the other hand, was very different. Johnson's samples had a much smaller standard deviation and varied mostly from moderately well sorted to very well sorted. The difference in sorting results may be attributed to the methods applied. Johnson's grainsize analysis was through a settling column and parameters were calculated using the 'method of moments' (Krumbein and Pettijohn, 1938, Friedman and Johnson, 1982) and sorting index of Trask (1932). The statistics generated by the mathematical method of moments are greatly affected by outliers in the tails of distribution (Blott and Pye, 2001), whereas Trask's formulae is most appropriate for the analysis of open-ended distributions, ignoring the tails of the distribution, which may or may not include extreme outliers (Blott and Pye, 2001).

Figure 6.3 shows selected examples of SEM images of individual quartz grains in the 1-2 phi fraction. The northernmost sample (O10) was characterised by low to high spherical angular to sub-rounded grains (Figure 6.3a). Quartz grains in sample O17, located offshore of Shoalhaven Heads (Figure 6.3b), were angular to sub-rounded, and slightly more angular and spherical than the ones in sample O10. Fresh surfaces from physical weathering, as well as medium chemical action were also observed in quartz grains in sample O17.

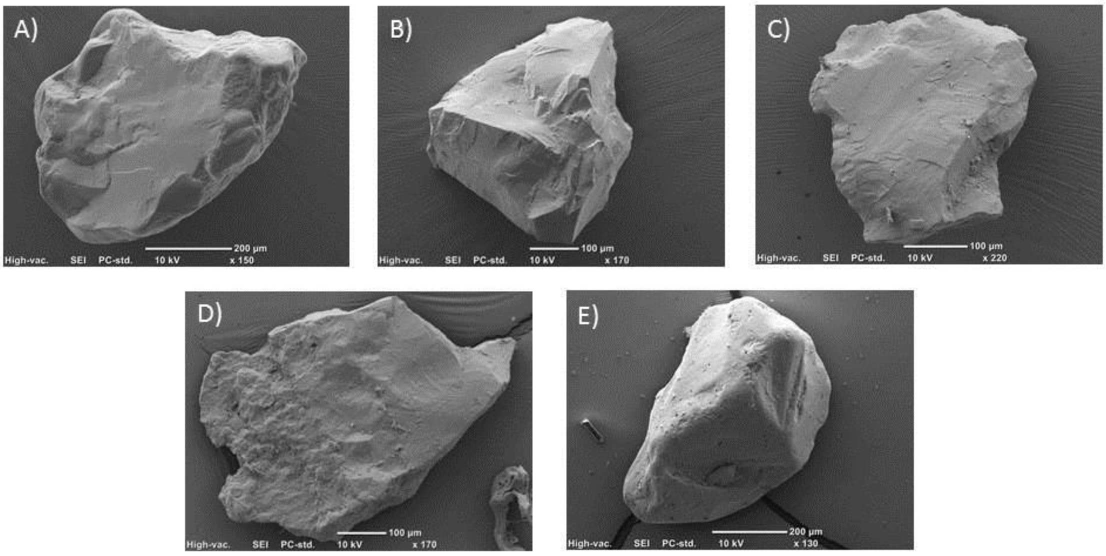

Figure 6.3 Selected examples of SEM images of quartz grains in the 1-2 phi fraction in nearshore samples. A) Sample O10 located off Seven Mile Beach; B) Sample O17 located off Shoalhaven Heads; C) Sample O29 located off Culburra Beach; D) Sample O37 located off Kinghorn Point; and E) Sample O41 located off Hammerhead Point. Images of all 16 quartz grains analysed in each nearshore sample are found in Appendix 9.

Comparing the roundness of nearshore and beach quartz near Shoalhaven Heads, grains from sample O17 were much less angular than grains from sample B22 (Figure 5.4c), indicating that the former is significantly more mature than the latter, which may reflect the abrasion and reworking history associated with these grains.

At Culburra (sample O29), grains were angular to sub-rounded (Figure 6.3c). Fresh surfaces were present in the angular grains implying recent fracturing. Individual grains were low to highly spherical, however, most grains fell in between these two extremes. As expected, the grains present in this sample were more angular than the beach sand found at Culburra Beach (B14) (Figure 5.4e), since their depositional environment is less energetic than the swash zone. It is also reasonable to think that some of the quartz grains were derived from the nearby rock reefs, due to its proximity and shape.

Individual quartz grains had a mix of low and medium sphericity, and were very angular to sub-angular (Figure 6.3d) off Kinghorn Point (sample O37). Individual grains were sub-angular to rounded in sample O41, located further south off Hammerhead Point (Figure 6.3e). Fresh surfaces were observed in only one of the three sub-angular grains. No specific pattern was observed for sphericity, as grains of both low and high sphericity were equally present in the sample. Surprisingly, in terms of roundness, individual grains in sample O37 were much more angular than the ones in sample O41, which were almost as rounded as the grains in the adjacent beach sample B7 (Figure 5.4g). Since sample O37 was located very close to the rock reefs off Kinghorn Point, it is likely that some of the quartz grains derived from the underwater reefs.

The use of SEM images of quartz grains to differentiate nearshore sediments among the three embayments was not as successful as when SEM was applied to the estuarine and beach environments. Although the nearshore sample off Hammerhead Point (O41) showed marked differences to sample O37, located only 2 km away, no specific pattern could be found to differentiate nearshore sediments of Seven Mile Beach-Comerong Island from Culburra Beach. These complications are probably related to limited number (N = 5) of nearshore samples analysed using SEM and the fact that both Culburra and Warrain-Currarong embayments are surrounded by underwater rock reefs that mask the results and make it difficult to draw conclusions about the possible distinct nearshore sediment characteristics.

6.3 Mineralogy

Quartz concentration in the offshore samples, as shown by XRD, varied from 64.9 % at O46 to 90.6 % at O41, reflecting the abundance of carbonates in those two samples (Table 6.1). Carbonate concentration in offshore samples varied considerably according to the proximity of rock reefs, suggesting that the volume of carbonate sediments produced by *in situ* organisms is a function of rock reef area. Offshore reefs in the Seven Mile Beach-Comerong Island tertiary compartment are restricted to areas near Gerroa and Crookhaven Heads only, whereas nearshore/shoreface areas off Culburra and Warrain-Currarong beaches are surrounded by rock reefs. Carbonate minerals were almost absent (0.3 %) in front of Shoalhaven Heads (O17), where rock reefs are absent, and very abundant (26.4 %) near Currarong (O46), where rocky reefs provide substrate on which carbonate organisms to grow. Other samples abundant in carbonate include O2 (11.8 %), near Gerroa, O29 (10.5 %), at Culburra, and O37 (11.8 %), in front of Kinghorn Point. All samples with carbonate higher than 10 % are associated with underwater reefs. Surprisingly, carbonate content present at O52, located off Gerringong (north of the study area) and surrounded by rocky reefs, only constituted 3.8 % of the total minerals in that sample.

Table 6.1 Mineralogy of offshore surficial sediments (wt. %) of size fraction finer than 0 phi. Feldspars include orthoclase, albide, labradorite and microcline.

Sample	**Chi square**	**Quartz**	**Felds pars**	**Calcite**	**Mg Calcite**	**Arago nite**	**Musco vite**	**Illite**	**Kaoli nite**
O52	2.52	89.3	4.9	1.3	1.4	1.1	0	1.7	0.2
O2	2.62	66.5	14.5	3.3	5.7	2.8	5.2	1.1	0.9
O10	2.58	82.9	9.6	0.5	1.3	0	0.8	3.7	1.2
O17	3.01	87.4	8.2	0	0.3	0	0	2.9	1.2
O24	3.33	74.4	19.3	0	1.1	0	3.2	1.2	0.8
O29	2.54	77.5	9.8	2.5	4.4	3.6	0	1.9	0.3
O32	2.59	87.6	3.8	1.7	2.5	2.7	0	1.4	0.3
O37	2.79	70.9	14.6	3.3	5.1	3.4	0.2	2.2	0.3
O41	2.42	90.6	5.3	0.5	1	1	0	1.5	0.2
O46	3.1	64.9	6.6	7.4	10.2	8.8	0	1.2	1

Mg Calcite, a mineral found in fragments of organisms such as bryozoans, echinoderms and benthonic foraminifera (Milliman et al., 1974), was the only carbonate mineral present in all samples and constituted 10.2 % of the total minerals present in sample O46. Aragonite, the main mineral in gastropod and bivalve shells, was absent off Seven Mile Beach-Comerong Island apart from sample O2, but reached 8.8 % in sample O46, near Currarong. Calcite, a mineral found in calcareous red algae, dinoflagellates, brachiopods, and some arthropods, was concentrated in a similar pattern as Aragonite, absent or very low in the three samples at Seven Mile Beach-Comerong Island, south of O2, and higher near the reefs.

Feldspar totals ranged from 3.8 % (O32) near Warrain, to 19.3 % (O24) off Comerong Island. Orthoclase predominates among the feldspars in almost all samples and its abundance varied from 1.3 % to 4.7 %. Microcline, on the other hand, reached 13.7 % in the feldspar-rich sample O24, near Crookhaven Heads entrance. Albite was the main feldspar mineral in the northernmost samples off Seven Mile Beach-Comerong Island with concentration of up to 5.2 %. Labradorite abundance reached a maximum of 2.5 % at O37, and was absent in the samples off Warrain-Currarong. Feldspar concentration in sample O52 was less than 5 %, with orthoclase predominating with 2.8 %. The much lower concentration of feldspar in sample O52 compared with samples located in the nearshore of Seven Mile Beach-Comerong Island (O2, O10, O17 and O24), suggests that the Shoalhaven River is not the source of sediments found adjacent to Gerringong.

The feldspar and carbonate content in samples O37 and O41 provides a clue as to why the quartz grains of those samples are so different (Figure 6.3d and e) from each other. The high values for these minerals in sample O37 indicate that the sample was located near a rock reef and therefore, the quartz grains were immature and very-angular to sub-angular, whereas the low values for feldspar and carbonate content in sample O41, indicate that this sample was located considerably away from nearby rock reefs and therefore, distant from new sources of rock fragments.

Clay minerals were present in the nearshore samples in the form of Muscovite, Illite and Kaolinite. Clay mineral content varied from 4.1 % (O17) to 7.2 % (O2) at Seven Mile Beach-Comerong Island, and was less than 2.8 % in the nearshore sample collected near Gerringong, Culburra and Warrain-Currarong. Off Seven Mile Beach-Comerong Island, the highest content of clay minerals was associated with the decrease in mean grain size. Likewise the beach samples, nearshore samples composed of slightly finer sands (mean = 2.5 - 2.6 phi), located near Gerroa (O2) and Comerong

Island (O24), had more (up to 3.1 %) clay minerals than the coarser samples (mean = 2.2 phi) located off Shoalhaven Heads (O17). Muscovite had considerable concentrations of 5.2 % and 3.2 % in samples O2 and O24, respectively, and was absent in 6 of the other nearshore samples. Illite and Kaolinite were present in all samples. Illite concentration ranged from 1.1 % to 3.7 %, whereas Kaolinite abundance had a much lower range of 0.2 % to 1.2 %.

In general terms, the mineralogical analysis points to two different types of sediments in the nearshore of the Shoalhaven coastal compartment. The carbonate-poor, clay mineral-rich sands off Seven Mile Beach-Comerong Island, sourced by the Shoalhaven River, and the carbonate-rich, clay mineral-poor sands off Culburra and Warrain-Currarong beaches. The low concentration of feldspars and clay minerals distinguish the sample collected near Gerringong from the ones off Seven Mile Beach-Comerong Island, suggesting no major transport of sediments leaking from the Shoalhaven coastal compartment to the north.

6.4 Nearshore bathymetric volume change off Shoalhaven Heads

When the mouth of the Shoalhaven River is breached at Shoalhaven Heads (Figure 6.4a), sediments accumulate in the nearshore, in the form of a broad crescentic river-mouth bar. With time, especially during reduced outflow, waves constrict the outlet, migrating sands into the channel (Wright, 1977), until a complete seal is formed and the beach is restablished (Figure 6.4b).

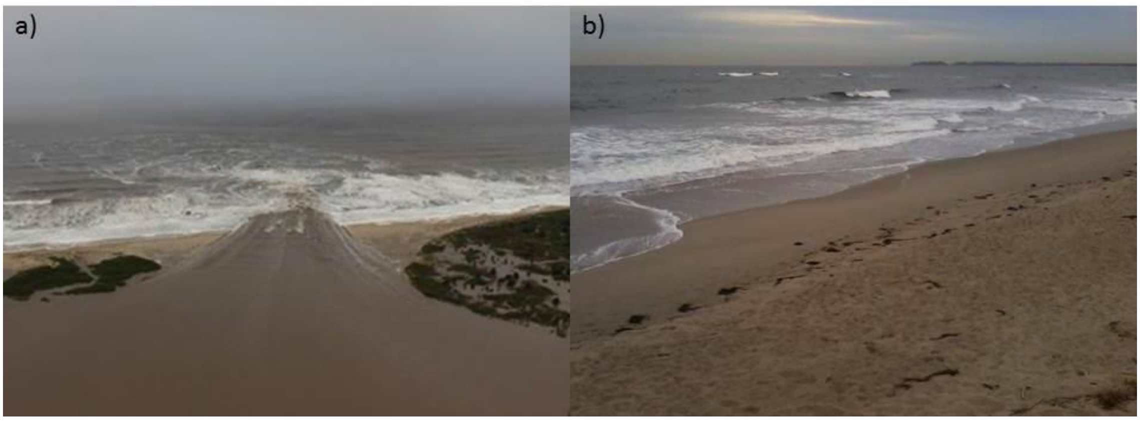

Figure 6.4 Sediment discharge off Shoalhaven Heads. a) Discharge into the nearshore hours after a breaching event on 27/08/2015. Photo by Colin Douch; b) Photo taken at Shoalhaven Heads looking south towards Crookhaven Heads (which can be seen on the far background) on 18/07/2013. Waves can be seeing breaking on the sand bank formed in the nearshore (background) by the flood event that happened 19 days before and breached Shoalhaven Heads.

The bathymetric change experienced off Shoalhaven Heads (Figure 6.5) has helped to understand the volume of sediment transported to the nearshore over time. In 1981, Shoalhaven Heads was closed, but in 1980 the area was still closing from the opening that happened during the 1970's, and therefore, a large amount of sediment was deposited in the nearshore down to 18 m deep.

Between 1981 and middle 1988, the entrance remained closed, and only opened again in the second half of 1988. It is expected that during this time much of the sediment deposited in the nearshore adjacent to Shoalhaven Heads had been reworked and redistributed alongshore by wave action and part of it moved across-shore to the beach berm and also back into the estuary by wind processes. Gordon (2013) estimated that 400,000 m^3 of sand was involved in the re-formation of the entrance from 1981 to 1985.

The survey carried out in April/1989 after the breaching event in 1988, covered a much more restricted area than the survey of 1981. Once again, a large volume of sediment was deposited in the nearshore, but this time the convex form deposited was located slightly more to the south. This time, approximately 440,000 m^3 of sediment was deposited in the nearshore when compared to the same area in the 1981 survey.

By 2006, a considerable amount of sand previously observed in the nearshore adjacent to Shoalhaven Heads has been moved away. This time a loss of approximately 1,640,000 m^3 occurred from the same area covered in 1989. Shore-parallel isobaths down to 8 m of depth suggest that the sediment was transported from shallow water by wave action, whereas non-parallel deeper isobaths suggested that remains of the nearshore deposit still existed down to 16 m of depth after 17 years. Nevertheless, the total nearshore area between Shoalhaven Heads and Crookhaven Heads showed an accretion of approximately 1,065,000 m^3 of sediment between 1981 and 2006.

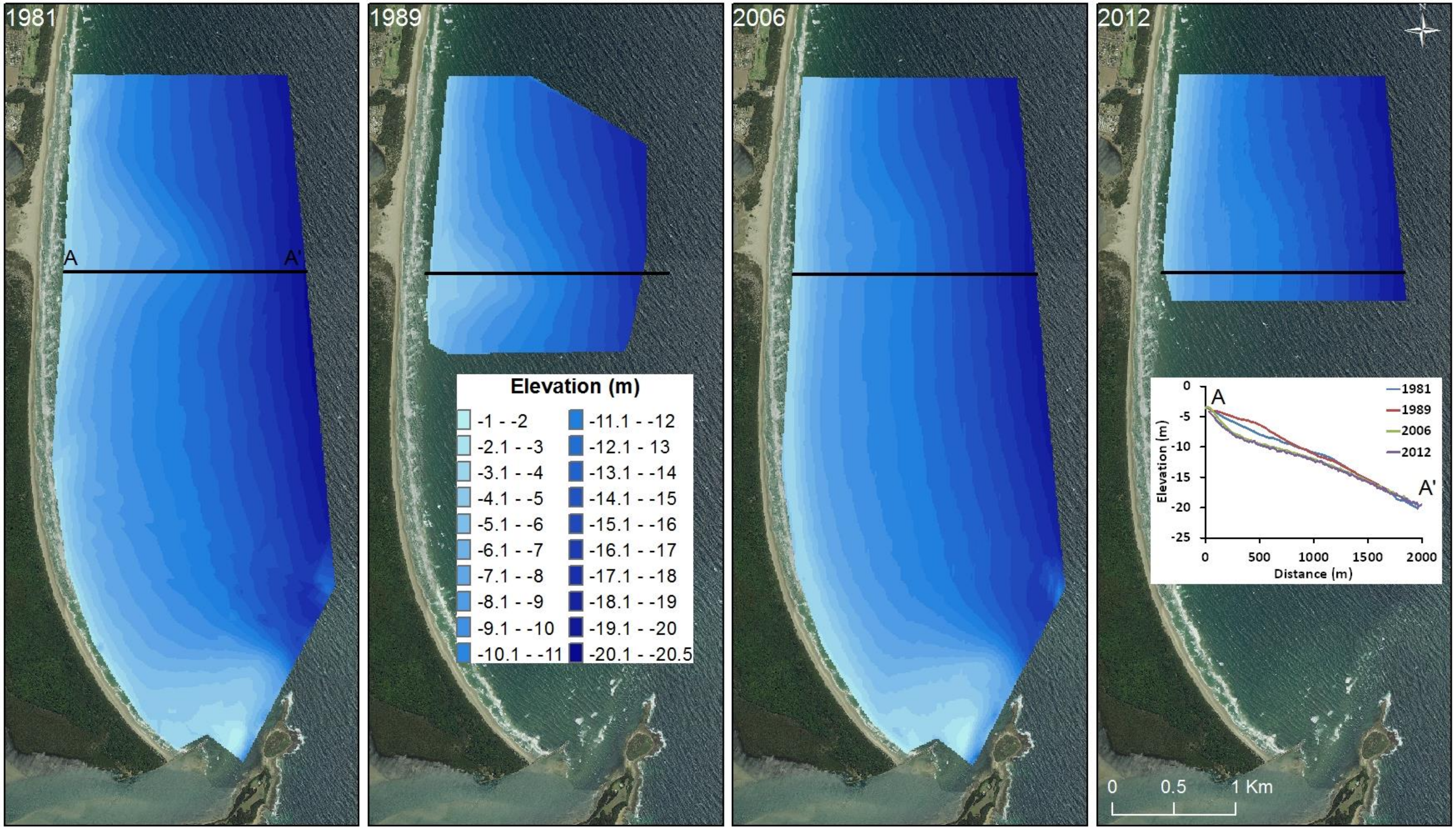

Figure 6.5 Bathymetric variation in 1981, 1989, 2006 and 2012 between Shoalhaven Heads and Crookhaven Heads. Nearshore profile is shown in black line and plotted on the right hand side. Background imagery © NSW Government. Office of Environment and Heritage (OEH) 2014

The next bathymetric campaign taken in 2012 covered a much more restricted area than the 1981 and 2006 surveys and also did not extend further south as in 1989. However, the 2012 campaign showed isobaths were much more shore-parallel than in 2006, implying that the sand deposited in the nearshore during the flood event was transported and distributed alongshore throughout the embayment and across-shore to the beach. Compared to the same area in 2006, approximately 400,000 m^3 of sediment was transported from the area by 2012. The graph presented on the right hand side of Figure 6.5 shows the variation of the nearshore deposit over the years at cross-section A-A'.

The volumetric changes indicate that a considerable amount of fluvial-estuarine sediments have been deposited in the nearshore since 1981 and at least 1,065,000 m^3 were discharged by the Shoalhaven River and deposited in the nearshore area between Shoalhaven Heads and Crookhaven Heads, as discerned from the observed accretion that occurred between the 1981 and 2006. Non-parallel depth contour lines deeper than 10 m, in the 2012 bathymetric survey, suggest that remaining sediments from previous breaching events still exist in the Seven Mile Beach-Comerong Island nearshore, and therefore, further beach accretion can be expected once wave-driven transport takes place and sediment is reworked to the beach.

6.5 Shoreface sand supply and availability

Coastal barrier initiation started towards the end of Postglacial Marine Transgression with the reworking of marine sand from the inner continental shelf (Thom et al., 1978). This depositional model responded to the disequilibrium conditions of the inner shelf to the sea-level highstand and involved a shoreface supply of sands to the beach (Roy and Thom, 1981) that resulted in steepening/lowering of the shoreface surface. The hypotheses for shoreface sand supply proposed by Roy and Thom (1981) involve either the erosion of a convex sediment bulge situated on the upper shoreface or the lowering of the entire shoreface.

Long-term shoreface supply to beaches is undetectable on annual and even sub-decadal time scales and is masked by more rapid cyclical changes (Cowell et al., 1995), because the supplied volume is negligible compared to the volume of sand involved in the beach erosion and recovery cycles. However, the effect of this net supply has direct implications for coastal management, as it can offset other factors (Cowell et al., 2001), promoting shoreline stability (Kinsela et al., 2016) and even enabling progradation if shoreface supply dominates over littoral sediment losses (Cowell et al., 2001).

Shoreface sand supply is extremely difficult to measure in the field but evidence of it has been presented for several coastal environments around the world (Kaminsky et al., 1999, Stive et al., 1999, Anthony, 2013, Aagaard, 2014), including the NSW coast (Cowell et al., 1995, Patterson, 2013, Kinsela et al., 2016). Rates of shoreface sand supply to beaches indicated from various lines of evidence are typically on the order of 10^0 $m^3/m/y$ (Cowell et al., 2001). This volume corresponds to a lowering of the shoreface by only a few grain diameters per year (Cowell et al., 2001). Site-specific average rates of shoreline supply using radiometric dating of prograded barriers for Moruya Beach (Thom, 1984), located 120 km south of Nowra, and Tuncurry Beach (Roy et al., 1994), located 340 km north of Nowra, calculated by Cowell et al. (2001) give an estimated rate of 3.3 $m^3/m/y$ and 4.3 $m^3/m/y$, respectively.

After centuries of offshore supply in order to re-establish an equilibrium condition following the end of Postglacial Marine Transgression, the shoreface sand reserves depleted, the rate of barrier growth declined and eventually ceased (Roy et al., 1980) in southeastern Australia, after 3000 y BP. However, it has been postulated that a re-activation of shoreface supply of sand might have occurred in the late Holocene, due to the lowering of sea-level from +1.5 m to present level, in a process called forced regression, and therefore, a shoreface sand supply on the order of 1-2 $m^3/m/y$ may persist on some NSW beaches (Kinsela et al., 2016). In this case, an average contribution of 17,000 to 34,000 $m^3/$ y of sand would have been added to Seven Mile Beach-Comerong Island in past decades. Potential volumes of sand supplied by the shoreface to the beach for the three embayments under different supply rates are shown in Table 6.2.

Despite the uncertainties in terms of current rates of supply, if shoreface sand contribution to the beach is still occurring in the Shoalhaven coastal compartment, it may be partially responsible for the beach accretion and shoreline progradation experienced in the past decades at Seven Mile Beach-Comerong Island (Figure 5.10), and to a greater extent to most of the shoreline displacement at Culburra (Figure 5.11) and Warrain-Currarong (Figure 5.12) beaches, once these two embayments receive no major fluvial contributions.

Table 6.2 Potential shoreface supply volumes (m^3/y) for the three embayments in the Shoalhaven coastal compartment based on shoreface supply rates between 0.5 and 3 $m^3/m/y$

Embayment	Beach length (m)	Shoreface supply rate ($m^3/m/y$)					
		0.5	**1**	**1.5**	**2**	**2.5**	**3**
Seven Mile Beach-Comerong Island	17,000	8,500	17,000	25,500	34,000	42,500	51,000
Culburra	3,600	1,800	3,600	5,400	7,200	9,000	10,800
Warrain-Currarong	11,300	5,650	11,300	16,650	22,600	28,250	33,900

Regardless of the current rate of shoreface supply, it is also clear that rates must be different for the three embayments reflecting the degree of exposure from the predominant wave direction and storms, and the availability of sand in the shoreface. Southerly and southeasterly storms refract at Beecroft Peninsula, and therefore, less energy is available to entrain sediments on the Warrain-Currarong shoreface than in the nearshore of Culburra and Seven Mile Beach-Comerong Island. In terms of availability of sand, the extension of submerged rocky reefs between Crookhaven Heads and Beecroft Peninsula (Figure 6.1) is an indicator that not much shoreface sand exists adjacent to Culburra and Warrain-Currarong beaches. In fact, the seismic surveys reported by Roy and Ferland (1987) point to a thick sandy shoreface accretion wedge along Seven Mile Beach-Comerong Island, extending for 2-3.3 km offshore and pinching out in water depths of 23-25 m, whereas, south of Crookhaven Heads, the shoreface accretion wedge is poorly developed or absent, with only pockets of sediment among the numerous rock reefs (Figure 6.6).

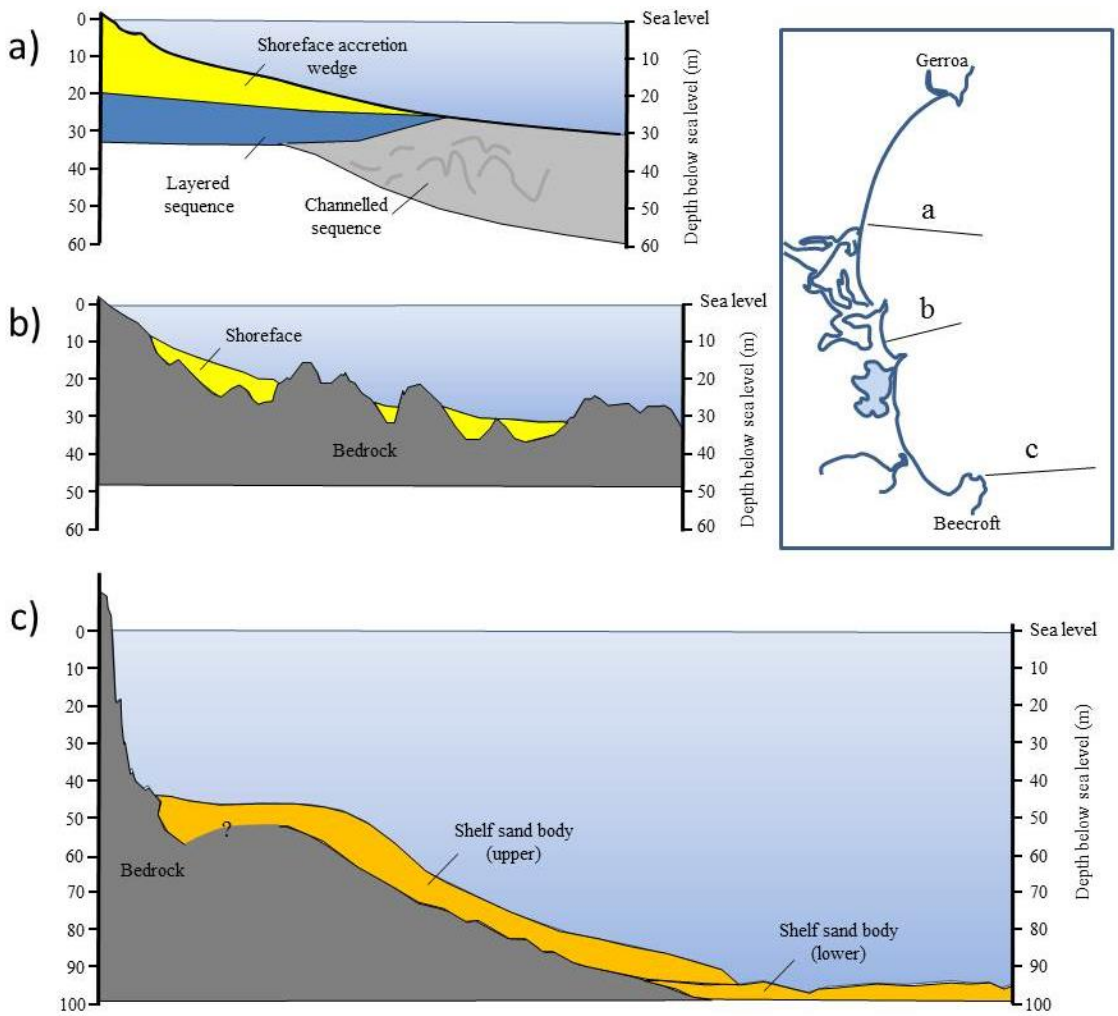

Figure 6.6 Seismic profiles off Shoalhaven Heads (a), Culburra Beach (b), and Beecroft Peninsula (c), modified after Roy and Ferland (1987). a) The shoreface accretion wedge forms a seaward extension of the Holocene prograded barrier. This facies is underlain by a sub-horizontally layered sequence possibly composed of estuarine muds. A channelled sequence occurs in the subsurface beneath much of the inner shelf and the chaotic bedding probably represents fluvial channeling by the meandering Shoalhaven River during lower sea-levels; b) Thin cover of sediment between outcropping bedrock with likely Pleistocene sediments shallowly underlying the shoreface; c) Two shelf sand bodies occuring off Beecroft Peninsula. The toe of the upper sand body onlaps the landward edge of the lower one. Length of track lines inferred from Figure 2 in Roy and Ferland (1987).

6.6 Headland bypass

The feasibility of headland bypass of sediments was assessed based on the available soundings for the Shoalhaven coastal compartment and new bathymetric surveys off Currarong and Gerroa (Figure 2.5) conducted specifically for this project.

There is no evidence of sediment supply, driven by northerly littoral drift, bypassing Beecroft Peninsula, at the southern end of the Shoalhaven coastal compartment. The seismic and sedimentary surveys published by Roy and Ferland (1987) indicated the existence of two large, thick shelf sand bodies (SSB) located immediately seaward of the bedrock cliffs of Beecroft Peninsula (Figure 6.6). The toe of the upper sand body onlaps the landward edge of the lower sand body that sits in water depths of approximately 100 m. The upper SSB is located quite deep (> 40 m depth) and it abuts against the rock reefs forming Sir John Young Banks. Even if the surface sediments are remobilized by storm waves, it is likely that the obstacle imposed by the rocky reefs (Figure 6.7) would impede or trap their transport towards the Warrain-Currarong embayment. Nevertheless, Ferland (1990) identified a complex distribution of surficial sediments in the SSB and noted that sediment groups from there are generally different from ones in the embayment to the north.

The headland of Black Head, located at the tip of Gerroa, extends for several hundred meters offshore, providing a physical obstacle for the northerly littoral drift towards Gerringong (Figure 6.8). The area is surrounded by rock reefs that extend as far as 2 km to the southeast, and at least 1.2 km to the southwest of Black Head, that hinder sediment from escaping the Shoalhaven coastal compartment. Shallow rocks (3-4 m depth) to the southwest of the subaerial platform form a 500 m-long rock barrier that sits 3-4 m below mean sea-level. This rock barrier submerges to 17 m of depth in the topographic low area indicated in Figure 6.8, before rising to 8 m of depth, 300 m to the southwest. It is envisaged that only during extreme southerly storms could resuspended fine sediments from the nearshore bypass Black Point towards Gerringong.

No detailed bathymetry exists for the area immediately south of Penguin Head, and therefore, the assessment of sediment bypass at that location driven by northerly littoral drift becomes difficult. However, judging from the east-west orientation of the rock platform and the amount of distinguishable rock reefs using aerial photographs to the south and east of Penguin Head, it is conceivable that none or very little sediment bypass occurs from Warrain to Culburra, during southeasterly storms. Nearshore and beach sediment size at Warrain is composed of medium sand and therefore, entrainment and transport velocities have to be quite high to bypass the approximately 400 m of rocks that form the southern side of the platform. Sediment bypass in the other direction, from Culburra to Warrain, during northeasterly storms is also most likely negligible due to the orientation and extension of the rock platform (approximately 700 m on the northern side), and also the extension of rock reefs around to the north of Penguin Head (Figure 6.9).

The rock platform of Crookhaven Heads extends for approximately 1 km and has a different orientation than Penguin Head. The north-northeasterly orientation of Crookhaven Heads facilitates the transport of sediments from Culburra towards the nearshore of Comerong Island driven by a south or southeasterly swell. However, this is unlikely to happen due to the refracted wave pattern even during southerly or southeasterly swells, when wave angle of incidence on the northern part of the beach tends to be almost parallel to the beach orientation, minimizing longshore transport. High velocities are also required to transport the medium sand size and even in the case of some sediment escaping the beach, the underwater reef crevasses would act as a sediment trap impeding Culburra sands reaching Seven Mile Beach-Comerong Island. Nearshore sediment transport in the other direction is difficult to occur due to the orientation of the headland that would direct sediments towards the Crookhaven channel, instead of towards Culburra.

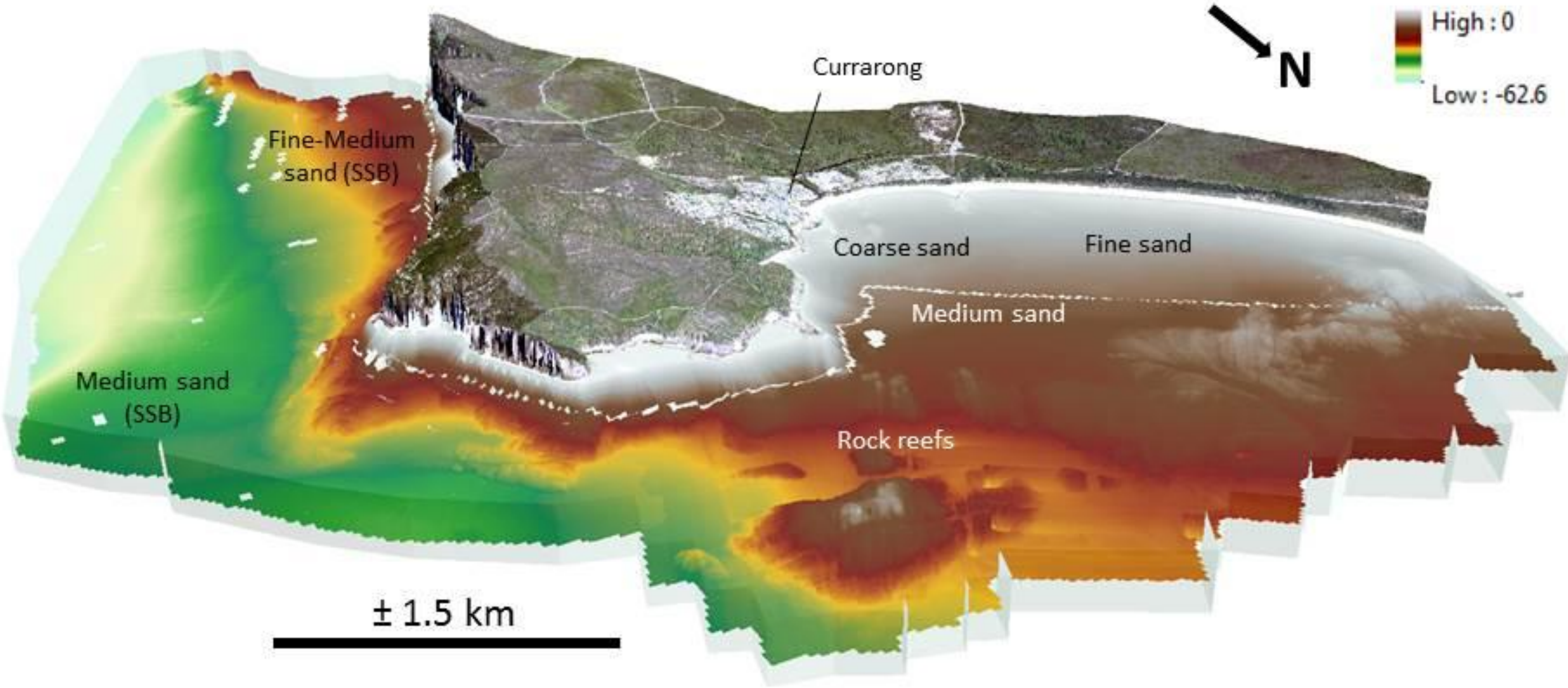

Figure 6.7 3D visualization of Beecroft Peninsula showing physiography and depths of the shoreface-inner continental shelf. Adjacent rock reefs form a natural barrier to sediment transport from the shelf sand body (SSB) to the Shoalhaven coastal compartment. DEM constructed using combined LiDAR data, singlebeam and multibeam bathymetry (Figure 2.5). SSB sediment information extracted from Ferland (1990). Background imagery © NSW Government. Land and Property Information (LPI) 2013; Bathymetric data © NSW Government. Office of Environment and Heritage (OEH) 2014; © Commonwealth of Australia (Geoscience Australia) 2009.

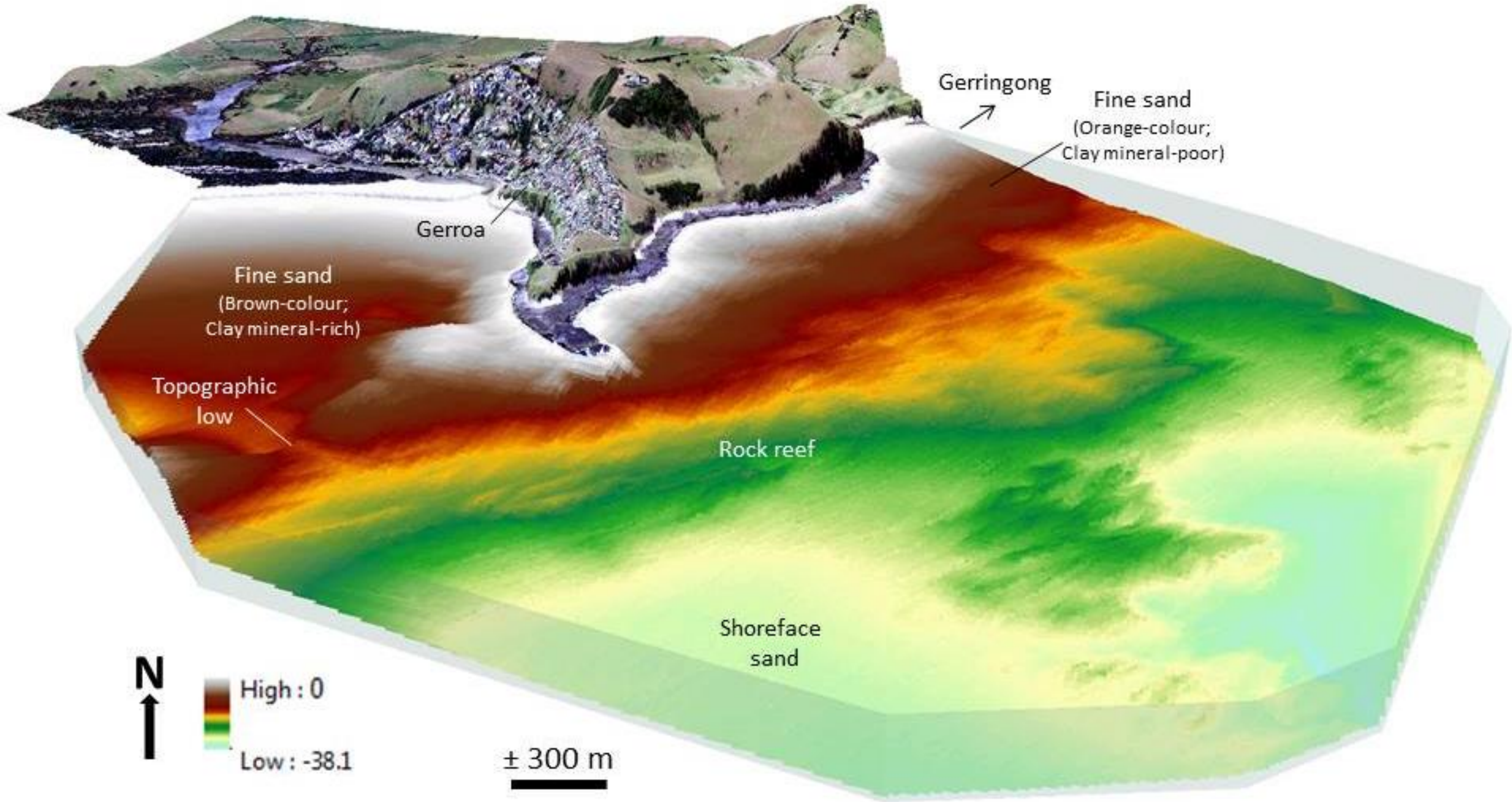

Figure 6.8 3D visualization of Gerroa showing physiography and depths of the shoreface-inner continental shelf. Subaqueous rock reefs off Black Head form a natural obstacle to sediment transport from Seven Mile Beach towards Gerringong (shown by an arrow). DEM constructed using combined LiDAR data and singlebeam bathymetry (Figure 2.5). Background imagery © NSW Government. Land and Property Information (LPI) 2013; Bathymetric data © NSW Government. Office of Environment and Heritage (OEH) 2014.

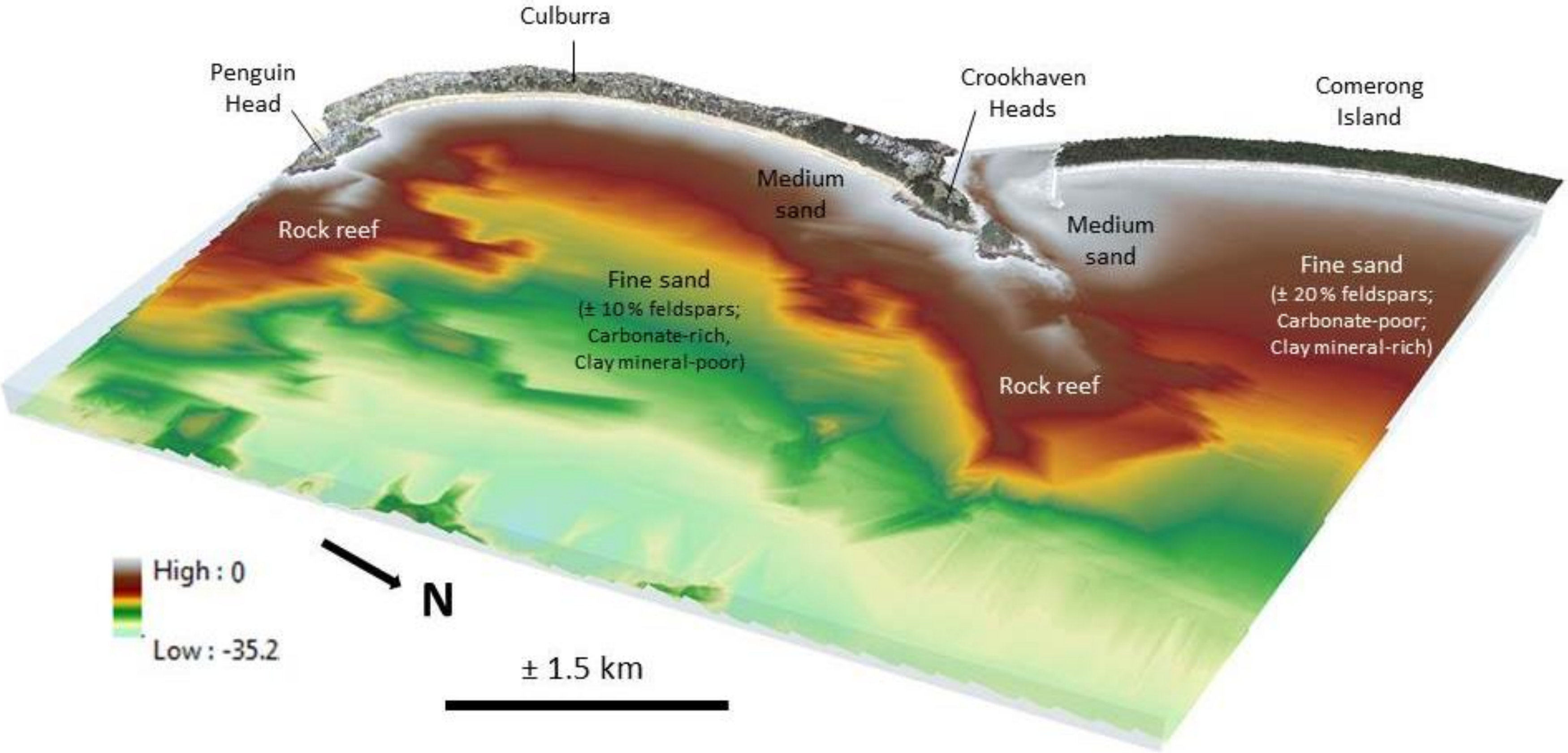

Figure 6.9 3D visualization of Culburra showing physiography and depths of the shoreface-inner continental shelf. Subaqueous rock reefs off Crookhaven Heads and the northern part of the rock reef off Penguin Head. DEM constructed using combined LiDAR data, singlebeam and multibeam bathymetry (Figure 2.5). Background imagery © NSW Government. Land and Property Information (LPI) 2013; Bathymetric data © NSW Government. Office of Environment and Heritage (OEH) 2014.

6.7 Summary

The Shoalhaven is a closed coastal compartment. No evidence of sediment contribution from the south exists and headland bypass around Black Head, with possible leakage of sediments towards Gerringong, is most unlikely, although the fine fraction present in the deeper sample retrieved near Gerringong suggests that some leakage of sediment may occur sporadically from the Shoalhaven coastal compartment towards Gerringong. Within the Shoalhaven coastal compartment itself, the orientation of Crookhaven Heads, favours the northerly transport of sediments from Culburra to Comerong Island, despite the absence of sedimentological evidence. Transport in any direction around Penguin Head is probably impeded by the obstacle imposed by the orientation of the platform.

Medium to fine sand occurs in the nearshore of both Seven Mile Beach-Comerong Island and Culburra beaches, whereas off Warrain-Currarong, samples varied from very coarse sand near the rocky reefs, to very fine sand in the deeper areas off Kinghorn Point. Despite some similarities to the adjacent beach samples, roundness and sphericity of quartz grains were likely influenced by the lower energy environment and proximity of rock reefs. Two different groups of sediments were distinguished based on mineralogy: the carbonate-poor, clay mineral-rich sands off Seven Mile Beach-Comerong Island sourced from the Shoalhaven River, and the carbonate-rich, clay mineral-poor marine sands off Culburra and Warrain-Currarong beaches.

As a general rule, carbonate concentration in offshore samples increased with proximity to the rock reefs, suggesting that the total volume produced by carbonate-secreted organisms in the Shoalhaven coastal compartment is a function of the areal extent of rock.

The nearshore bathymetric change that occurred off Shoalhaven Heads in 1981, 1989, 2006 and 2012 has helped to estimate the volume of sediment transported to the nearshore over past decades. In 1981, months after the closing of Shoalhaven Heads and the re-establishment of the beach-berm, a broad crescentic river-mouth bar existed in the nearshore, formed by the transport of fluvial-estuarine sediments. Eight years later, at least 440,000 m^3 of extra sediment was added to the coastal compartment, when compared to 1981. By 2006, at least 1,065,000 m^3 of sediment was added to the nearshore adjacent to Shoalhaven Heads and Crookhaven Heads in relation to 1981.

This volume, however, can be considered conservative, and the volumetric contribution may have been much higher than the bathymetric difference observed during these two surveys, as sediment might have been distributed throughout the embayment and across-shore to the beach. Non-parallel depth isobaths deeper than 10 m, in the 2012 bathymetric survey, suggest that remaining sediments from previous breaching events still exist in the Seven Mile Beach-Comerong Island nearshore, and therefore, future beach accretion can be expected in this tertiary level compartment, as wave and current-driven transport takes place and sediment is reworked to the beach.

A less apparent process on annual or sub-decadal time scales that provides significant quantities of sand from the shoreface to the beach on the order of 1-2 m^3/m/y might be occuring at Seven Mile Beach-Comerong Island, due to the existence of a thick shoreface sand accretion wedge, and to a lesser extent at Culburra and Warrain-Currarong beaches, due to extension of rock reefs. In this case, a contribution of approximately 17,000 to 34,000 m^3/y of sand to the northernmost compartment, and a significant smaller volume to the other beaches might have been occurring over past decades, with clear implications for the sediment budget.

Chapter 7: The sediment budget of the Shoalhaven coastal compartment

This final chapter discusses propositions raised in the conceptual sediment budget framework outlined at the end of Chapter 1, which were subsequently investigated in chapters 3 to 6. It starts with a discussion of the sediment budget for the Shoalhaven estuary and then, a budget for the coastal compartment is presented and discussed. This chapter also provides a critical discussion of the work completed, comments on the contribution of this project to wider literature, and makes recommendations for future potential research and management considerations. Finally, a synthesis of the findings for the Shoalhaven coastal compartment, in terms of sediment volumes, transport rates and pathways is presented in the last section.

7.1 Coastal budget

The conceptual framework for the Shoalhaven coastal compartment in the introductory chapter identified the existence of three tertiary level compartments within the secondary level compartment and also indicated the possible sedimentary contributions, losses and exchange areas to the study area (Figure 1.2). Six different sediment sources, four sediment sinks and two exchange area components were identified to influence the way that Seven Mile Beach-Comerong Island, Culburra Beach and Warrain-Currarong Beach behave (accretion or erosion) in regards to sediment contribution or losses.

As demonstrated in Chapter 6, longshore transport from south of Beecroft Peninsula into the compartment (source component F in Figure 1.2) and northward of Black Head towards Gerringong (sink component J) were considered negligible. The lack of sediment transport into the compartment was inferred from the physical obstacle imposed by the reef rocks adjacent to Beecroft Peninsula that obstructs bypassing and the shoreward transport towards Currarong. Furthermore, the depths at which the inner shelf sand body sits hinder sediment entrainment. Nevertheless, whereas it is likely that no significant sediment is added to the Shoalhaven coastal compartment via bypassing of Beecroft Peninsula, further evidence supporting this statement is needed. At Black Head, near Gerroa, the reef extends considerably seawards inhibiting the transport of sediments from the Shoalhaven compartment towards the north. Visual inspection of the nearshore sediments located near Gerringong indicated a very different type of sand from the one observed at Seven Mile Beach-Comerong Island, although the fine fraction in one of the samples suggested that some northward leakage of sediment may occur sporadically. A qualitative look at the swash sand (beyond the scope of this thesis) located at Werri Beach, 2 km north of the samples collected in the nearshore near Gerringong, showed that quartz grains are stained, suggesting no bypass from Seven Mile Beach-Comerong Island into Gerringong. Therefore, for the purpose of the schematization of the budget, the possibility of leakage of fine sands from Gerroa to Gerringong under normal conditions was considered negligible too.

Assuming that the Shoalhaven compartment receives no alongshore contribution from the south and loses negligible amounts to the north, the secondary level compartment can be considered a closed compartment. However, during flood events like the ones that happened in June/2013 and August/2015, the compartment may become leaky, with the espisodic loss of material. In the June/2013 storm event (Figure 7.1), the breaching of Shoalhaven Heads transported fine sediments out of the secondary level compartment bypassing Black Head and Beecroft Peninsula.

The Landsat image acquired on 30/06/2013, one day after the breaching event at Shoalhaven Heads, shows a plume of sediments in suspension reaching 9 km seawards of the entrance. This plume was transported southward for tens of kilometers by the East Australian Current before being caught by clockwise vortices south of Jervis Bay and eventually exiting the continental shelf waters. Within the Shoalhaven compartment, the concentration of sediments in the plume is much stronger towards Gerroa than Beecroft Peninsula. In the zoomed-in image on the right-hand side of Figure 7.1, the plume reaches Gerringong driven by the southeasterly (109°) wave direction during the storm (Table 5.2), whereas less turbid waters are observed in the nearshore between Crookhaven Heads and Currarong, despite the discharge of sediments caused by the breaching of Lake Wollumboola and the small creeks near Currarong.

Longshore transport within the three tertiary level compartments is an important factor redistributing the sediments. However, sediment exchange between these compartments (exchange component L in Figure 1.2) is believed to be negligible, due to the headlands and adjacent underwater reefs off Crookhaven Heads and Penguin Head. The latter is a west-east oriented headland between Warrain and Culburra beaches obstructing the northward transport during southerly and southeasterly swells, and southward transport during less common northeasterly swells. The headland at Crookhaven Heads, on the other hand, extends towards the north-northeast following a similar orientation to the northern part of Culburra Beach. Southward transport from Seven Mile Beach-Comerong Island towards Culburra Beach is impeded by the trap formed by the headland directing the sediments towards the Crookhaven channel, whereas, transport in the other direction, from Culburra Beach to Seven Mile Beach-Comerong Island, might be facilitated by the headland orientation, although it seems unlikely to occur. It appears plausible that there is no exchange of sediments between the tertiary level compartments. However, confirmation of this would require stronger supporting evidence than presently available.

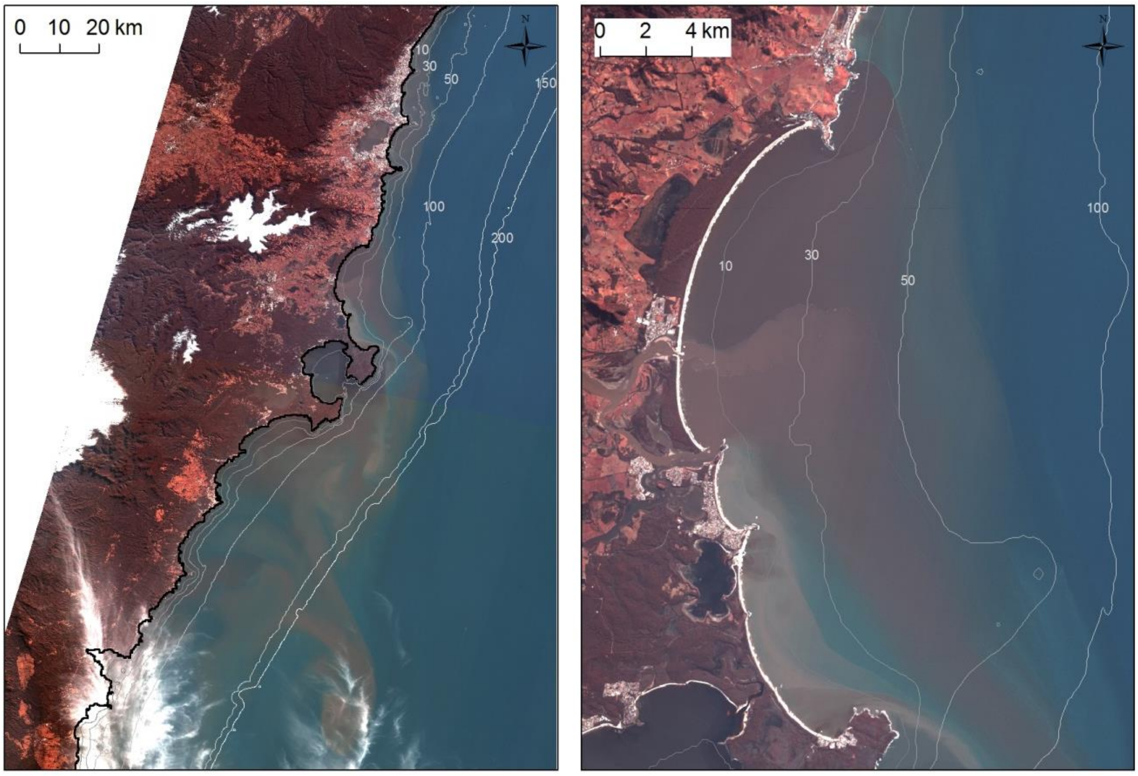

Figure 7.1 Landsat 8 false colour composite acquired on 30/06/2013, showing breached Shoalhaven Heads transporting fine material out of the secondary level compartment, towards both north and south directions (left). Zoomed-in image (right) showing detail of the plume bypassing Black Head and Crookhaven Heads. The beaches of Culburra and Warrain-Currarong were spared from most of the plume carrying fine sediments of the Shoalhaven River. Satellite imagery © LP DAAC.

Assuming there is no alongshore movement between embayments due to the headlands, it must be inferred that the losses and gains at these three closed tertiary level compartments are a product of cross-shore transport, headland erosion and *in situ* carbonate production sources.

Seven Mile Beach-Comerong Island, the northernmost tertiary level compartment, receives contributions from: the Shoalhaven River, its tributaries and the Crooked River (source component A in Figure 1.2); erosion in the lower end of the Shoalhaven estuary (source component B); erosion of Crookhaven Heads and Black Head headlands (source component C); *in situ* production by carbonate organisms on rock reefs adjacent to the headlands (source component D) and; the shoreface supply to the beach (source component E). Sediment losses are driven by: deposition (sink component G) at Shoalhaven estuary and Crooked estuary; mining around Pig Island (sink component H); and aeolian transport from the beach/foredune to the barrier (sink component I), whereas sediment exchange areas between both Shoalhaven estuarine entrances and the nearshore occur at Shoalhaven Heads and Crookhaven Heads (exchange component K).

In order to create a coastal budget for this tertiary level compartment, the Shoalhaven estuary needs to be balanced using sediment delivered by the Shoalhaven catchment, the values transferred to the nearshore and the volumetric estuarine change that occurred between 1981 and 2006. In terms of river contribution (source component A), the estimated average annual sediment yield (that incorporates extremes and prevailing conditions) from the Shoalhaven River and its tributaries (including Broughton and Crookhaven creeks) corresponds to 86,000 m^3/y or approximately 2,150,000 m^3 in the 25-year period between 1981 and 2006 (Figure 7.2). However, before reaching the coastline, sediments from the Shoalhaven River and its tributaries have to transit through the Shoalhaven estuary.

The role of South Coast estuaries as sinks of sediments has been emphasized by several authors (Bird, 1967, Davies, 1974, Roy et al., 2001). The infill of the Shoalhaven estuarine basin appears to have been largely complete by 3,000 y BP (Woodroffe et al., 2000) and nowadays, only 55.4 x 10^6 m^3 is available as accommodation space. Nevertheless approximately 400,000 m^3 of sediment was deposited downstream of Long Reach between 1981 and 2006. This value corresponds to the deposition of approximately 2,000,000 m^3 (sink component G) minus the erosion of 1,600,000 m^3 experienced in the lower part of the Shoalhaven estuary (source component B).

In terms of mining activities, there are two areas from which sediments are extracted. One located at Burrier, in the upper estuary, and another on the southern side of Pig Island. The Burrier Quarry is an aggregate extraction site on the floodplain run by Boral Resources Pty Ltd. Since no in-channel sediments are extracted, the average extraction of 100.000-500.000 m^3/y (EPA, 2013) should not be taken into account when calculating the budget. Shoalhaven Sand Pty Ltd extracts bed sediments from the area adjacent to the southern bank of Pig Island and processes into coarse sand. The operation has approval to extract a maximum of 100,000 tonnes of sand per year but has extracted on average 70,000 tonnes of coarse sand, over 7 years (APA, 2012). A volume of approximately 620,000 m^3 was extracted from the estuary (sink component H) according to the volumetric difference between 1981 and 2006 (Figure 4.3).

The limited space for sediment deposition within the Shoalhaven estuary favours transfer of sediments to the shoreface during flood events and therefore, sediment transport to the coast is not regular, but rather occurs in pulses. During low flow stage conditions, the entrance at Shoalhaven Heads is closed and the tidal effects transport marine sediments up the estuary through Crookhaven Heads and therefore, no sediments are discharged to the coast. When the fresh water flow increases but Shoalhaven Heads is not breached, it is likely that sediments are discharged to the nearshore through Crookhaven Heads. During storms events when Shoalhaven Heads is breached, not only sediments that were recently transported from the catchment, but also sediments eroded from the estuarine banks are transferred to the coast through both entrances.

The fact that Shoalhaven Heads entrance is closed most of the time creates interesting sedimentary dynamics that involve: i) deposition of marine sands around Old Man Island; ii) erosion dominating most of the Crookhaven channel; and iii) deposition of fluvial sediments happening along most of the Shoalhaven channel including Shoalhaven Heads, despite the gross losses that might occur during breaching events. Shoalhaven Heads lost at least 160,000 m^3 of sediments to the nearshore during the July/1988 breaching event, but gained 285,000 m^3 of material back between 1989 and 2006, plus another 61,000 m^3 of sediments until 2015, despite the breaching events that occurred during this time.

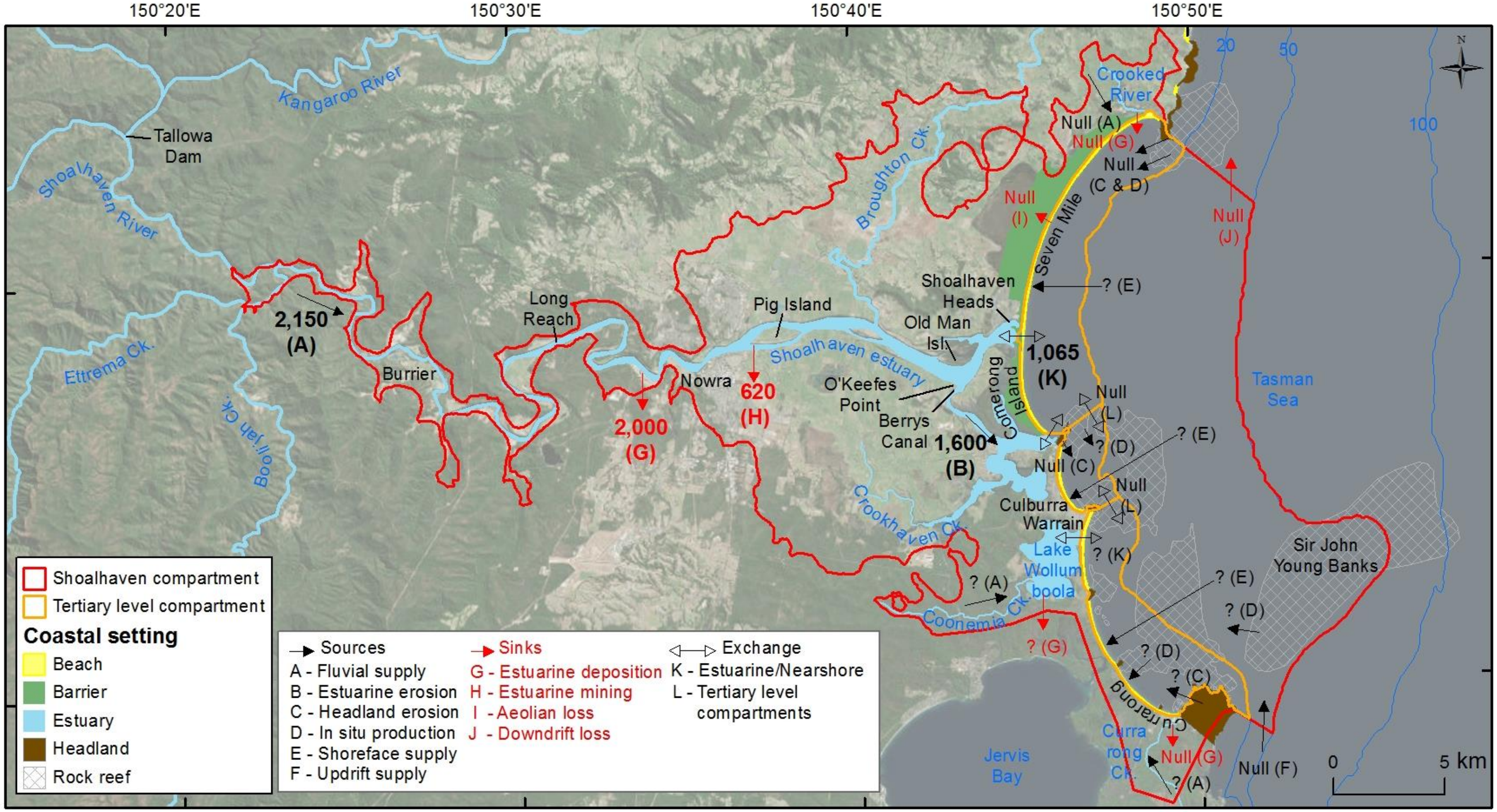

Figure 7.2 Sediment budget for the Shoalhaven coastal compartment based on values obtained between 1981 and 2006. Shoalhaven catchment contribution based on average annual fluvial estimations multiplied by 25 years. Volumes in 1,000 m^3. Question marks represent unknown volumes. Background imagery © LP DAAC.

During the last four breaching events when the Shoalhaven City Council artificially opened Shoalhaven Heads, the entrance remained open for less than nine months, with closing of the entrance starting immediately after the passage of the triggering weather event. The closing process transports sediments from the nearshore back to the estuary by narrowing the flow channel and choking the entrance, until a complete rebuild of the beach berm. Approximately 200,000 m^3 and 165,000 m^3 of sand from the beach berm was transferred to the nearshore, during the breaching events of 2013 and 2015, respectively, at Shoalhaven Heads. These volumes are equivalent to twice the estimated annual catchment delivery to the estuary. In the 2013 event, the return of most of the sand lost (200,000 m^3) to the nearshore happened in the next nine months that followed the opening event. After the sealing of the entrance, wind processes continue to transport sediments from the beach into the estuary, whereas the low flow velocities in the backwater behind the sealed entrance facilitates deposition of fine sediments between Old Man Island and the Shoalhaven Heads village.

The existence of flood-tidal deltas on the Crookhaven channel is a testimony to the flood-oriented net sediment transport moving marine sediments up the estuary, and therefore a sink for the coastal budget. During storm events a proportion of these sediments is transported to the nearshore/offshore, frequently exiting the compartment as happened in the event captured by the imagery in Figure 4.19. The volume transported is difficult to measure however, owing to the time interval between consecutive surveys and the safety and logistic issues for deploying equipment during storm events. Since not much alteration in the flood-tidal deltas could be observed in the images in Figure 4.19, sediment losses due to this process are considered negligible for the budget analyses.

The change experienced in the nearshore between Shoalhaven Heads and Crookhaven Heads determined by the bathymetric surveys of 1981 and 2006 accounted for at least 1,065,000 m^3 of sediment added to the coastal compartment. This volume can be considered conservative due to possible unknown volumes that might have been transported away from the area used for the volumetric calculations during this 25-year period. This source of sediments to the nearshore and the along and across-shore transport by waves that followed the deposition during the flood events implies that at least 1,065,000 m^3 of sediment (exchange component K) became available for beach accretion over 25 years. This volume would represent an addition of approximately 63

m^3/m of beach if equally distributed along the 17 km length of Seven Mile Beach-Comerong Island over 25 years.

Another aspect of the volumetric change in the nearshore is related to the time that it takes for the system to adjust after a major input of sediment. Apparently, it takes many years to redistribute the sediments adjacent to Shoalhaven Heads until a equilibrium state of shore parallel isobaths is achieved, especially in deeper waters. In 2006, 12 years after the closing of the entrance following a major breaching event, there was still a considerable discernible shoreface anomaly to be reworked by waves. This implies that it may take several years or even decades to see the complete beach response. Therefore, net beach volume increase along Seven Mile Beach-Comerong Island should be expected for years as sediments are redistributed, despite periodic interruption by storms.

When 1,065,000 m^3 discharged to the nearshore in 25 years is subtracted from the fluvial contribution (2,150,000 m^3), a positive balance of 1,085,000 m^3 is obtained. In the same period, the estuary experienced a net accretion of approximately 1,020,000 m^3, as a result of the deposition upstream of O'Keefes Point (2,000,000 m^3), plus the volume mined near Pig Island (620,000 m^3), minus the estuarine erosion between the entrances (1,600,000 m^3). The very close values of 1,085,000 m^3 and 1,020,000 m^3 can be considered equivalent, especially considering that not all the estuary was surveyed in 1981, and therefore, an extra fluvial contribution upstream of the Long Reach would increase the net accretion volume of 1,020,000 m^3 experienced by the estuary between 1981 and 2006.

Besides the technological limitations and associated errors mentioned earlier, offsets to this balance may also occur due to uncertainties associated with the exact amount of sediments discharged to the nearshore and also estimates of fluvial contributions between 1981 and 2006. The value of 1,065,000 m^3 discharged to the nearshore was calculated using only the volume difference between the two surveys in a restricted polygon area of the nearshore that did not include most of the northern part of this tertiary level compartment. This difference did not take into account the volume that escaped the polygonal area used for the DEMs and was possibly transferred to the beach and to the north of Shoalhaven Heads by longshore transport after the 1981 survey. For instance, if 300,000 m^3 of sediments were transported to the north between surveys, this would imply that 1,365,000 m^3 (1,065,000 m^3 + 300,000 m^3) were transferred to the nearshore. Besides, the volume that was added during the breachings between 1988 and 1994 is not known, due to lack of data, and it is impossible to estimate.

Regarding the fluvial discharge to the estuary, the estimations were mostly based on an 88 % trapping efficiency of Tallowa Dam calculated elsewhere (Boyd et al., 1977). If the trapping efficiency were 78 % or 83 % for instance, the estimated sediment delivery to the estuary would have been increased to approximately 157,000 m^3/y or 120,000 m^3/y, respectively and this would result in a volume of 3,925,000 m^3 (157,000 m^3/y x 25 years) or 3,000,000 m^3 (120,000 m^3/y x 25 years) instead of the 2,150,000 m^3. Moreover, it is known from hydrology that most of the catchment sediment yield occurs during flood events when water discharge drastically increases. Therefore, the fluvial contribution value of 2,150,000 m^3, obtained based on the average annual catchment yield multiplied by the 25-year period, might be considered an underestimation of the actual volume deposited by the river. Another argument favoring a larger amount of sediment being delivered downstream, is related to the substantial pre-existing volume of sediments that was deposited upstream of the estuary prior to the construction of Tallowa Dam, and would off-balance the budget calculations. Whereas these assumptions seem plausible, means to calculate are not feasible using the presented data alone.

Crooked River, the other water body in this tertiary level compartment, has a very small catchment size and no fluvial contribution from this river could be observed in the beach sediments near the entrance. Therefore, fluvial sediments from the Crooked River are not considered to make a significant contribution to the budget (source component A). In fact, the Crooked estuary may act as a small sink of beach sediments. Regardless of its sink role, the losses attributed to Crooked estuary can be considered negligible (sink component G) due to limited accommodation space available in such a small estuary in relation to this sediment–rich tertiary compartment.

Lithic to feldspathic sandstones from the Broughton Formation form the Black Head headland at Gerroa, whereas quartz-lithic siltstones from the Wandrawandian Formation occur at Crookhaven Heads. These sedimentary rocks are relatively resistant to erosion. Whereas some erosion can be observed or inferred from the existence of the rampart on the seaward margin of Black Head and subaerial weathering occurring on both headlands, the contribution in terms of sediment input to the compartment can be considered insignificant (source component C).

Biogenic contribution (source component D) is not an important source of sediments in the Seven Mile Beach-Comerong Island tertiary level compartment. In general, temperate underwater reefs, headlands and exposed rocks, support a diverse fauna which contributes significantly to the volume of sand in the beach and nearshore, following the breakdown of their skeletons. Biogenic contribution to beach and nearshore sands was insignificant due to the scarcity of rock reefs in proportion to a large influx of quartz and feldspars minerals. Rock reef areas are only located near Gerroa and Crookhaven Heads and are restricted to only 2 km^2 approximately, when compared to an area of approximately 37 km^2 of unconsolidated sediments within this tertiary level compartment. Nevertheless, near Gerroa, a nearshore sample in the lee of a reef had 11.8 % of carbonate content.

An attempt was made to calculate sediment loss from the beach to the foredune system at Seven Mile Beach-Comerong Island following the procedures of Kadib (1964), but the results were inconsistent when compared to the geomorphological characteristics of the adjacent barrier, and therefore, no volume estimations are presented here. In fact, most of the sediment removed from the beach is transported into the foredune or contributes to incipient foredune accretion and during storms is likely to be incorporated back into the beach and nearshore, without significant losses to the tertiary level compartment caused by aeolian processes (sink component I). Nevertheless, a very limited loss landward of the foredune is envisaged to have occurred over the past 40 years, but for the budget calculations, this is treated as negligible.

The coastal budget itself was balanced using the values transferred to the nearshore and the volumetric change experienced at Seven Mile Beach-Comerong Island between 1972 and 2013. The year of 1972 was chosen because it preceded the major storms of 1974 and 1978 that heavily eroded the beach and also because the aerial photographs covered the whole embayment, making possible to reconstruct the shoreline position.

The volumetric change was calculated using the average accretional area of four cross-sections (SH1-SH4) at Seven Mile Beach-Comerong Island, multiplied by the distance between them. In the calculation, it was assumed that the beach face (slope) remained the same whereas the beach prograded through time. The cross-sectional area was calculated using the shoreline displacement as plotted in Figure 5.10, multiplied by the height of the incipient foredune extracted from Figure 5.16. The volume of the beach to the north of SH1 and to the south of SH4 was calculated using the remaining beach length multiplied by half of the cross-sectional area.

Beach accretion at profiles SH1, SH2, SH3 and SH4 was 212 m^2 (4 m x 53 m), 274 m^2 (4 m x 69 m), 104 m^2 (6.5 m x 16 m) and 96 m^2 (4 m x 24 m), respectively, between 1972 and 2013 (Figure 7.3). The average accretion between profiles SH1 and SH2 was 243 m^2/m, whereas 189 m^2/m was obtained between SH2 and SH3, and 100 m^2/m between SH3 and SH4. A value of 106 m^2/m (half of SH1) was estimated northward of SH1, and 48 m^2/m (half of SH4) southward of SH4. These values multiplied by the respective lengths of the beach segments yield 68,900 m^3 (northwards of SH1), 801,900 m^3 (between SH1 and SH2), 1,351,350 m^3 (between SH2 and SH3), 355,000 m^3 (between SH3 and SH4) and 105,600 m^3 (southwards of SH4). The sum of these beach segments corresponds to a total accretional volume of approximately 2,680,000 m^3 between 1972 and 2013.

The approximate volume of 2,680,000 m^3 of sediment needed to reflect the changes experienced at Seven Mile Beach-Comerong Island in 41 years, implies that an extra 1,615,000 m^3 on top of the 1,065,000 m^3 (calculated previously for the period between 1981 and 2006) were provided to the system. This means that the amount of sediment residual from the coastal budget was possibly provided by a combination of factors that includes: i) the unknown volume added to the nearshore before 1981; ii) more sediments deposited in the nearshore following breaching events between 1981 and 2006; iii) the transport of sands from the nearshore deposit to the beach after 2006; and/or iv) a shoreface supply of sediments to the beach.

Judging from the magnitude of the 1970’s storms and the prolonged time that Shoalhaven Heads was opened before the bathymetric survey in 1981, it is very likely that most of the remaining 1,635,000 m^3 of sediments was deposited in the late 1970s and by 1981 had been redistributed outside the area of the nearshore surveyed. Nevertheless, without nearshore bathymetric surveys prior to 1981, this assumption can only be speculative and not quantitatively expressed.

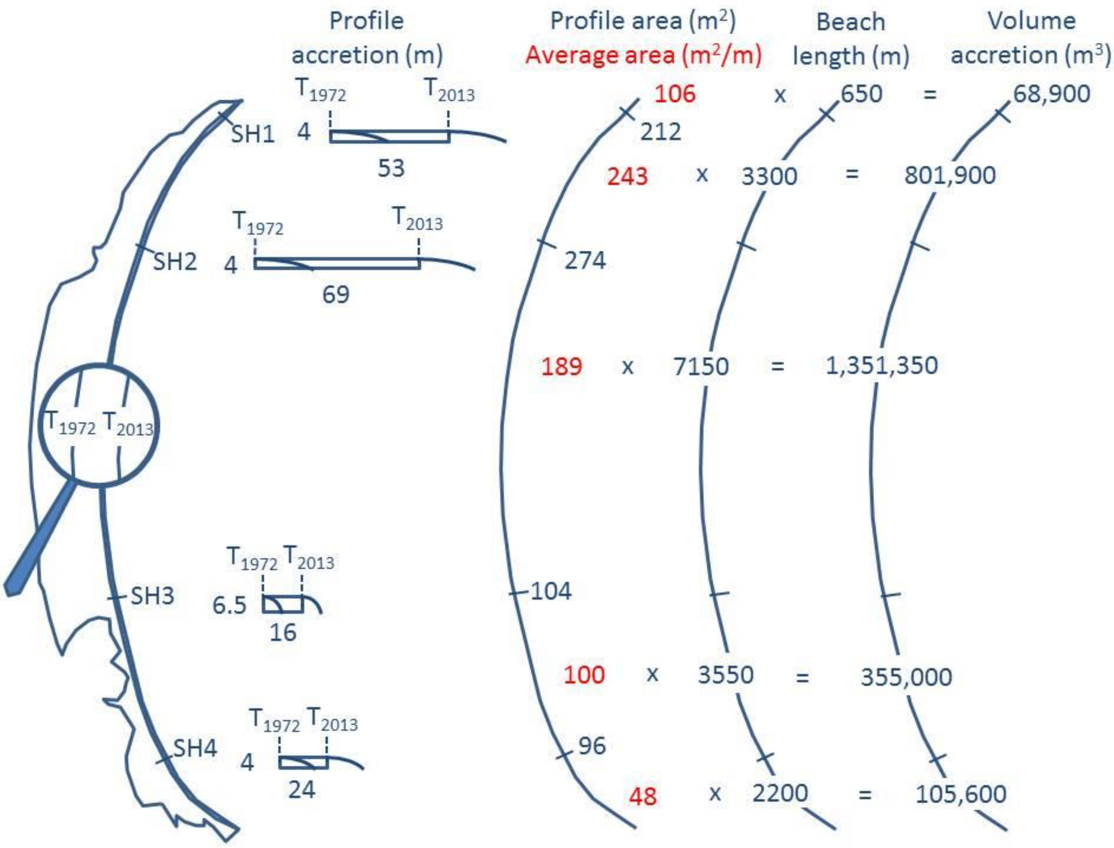

Figure 7.3 Volumetric accretion at Seven Mile Beach-Comerong Island based on average area accretion per meter of beach multiplied by the beach length. A total accretion of approximately 2,680,000 m^3 occurred between 1972 and 2013.

The reworking and transport of sand from the flood deposit in the nearshore to the beach after 2006 might explain some of the residual volume. The 2012 bathymetric survey showed much more shore-parallel isobaths and at least 400,000 m^3 of sand was transported and distributed alongshore and across-shore to the beach between 2006 and 2012. This volume alone, corresponds to approximately 25 % of the residual volume.

The deposition of more than 1,065,000 m^3 of sediments between 1981 and 2006 was discussed above, and it is very likely that significant volumes of sand escaped the surveyed area used for calculations. The implication for a higher volume deposited in the nearshore does not mean necessarily that the fluvial volume of 2,150,000 m^3 delivered to the estuary over 25 years is wrong. It may simply reflect the amount of sediment that existed in the 25 km of freshwater river course upstream of the estuarine limit that became depleted of sediment after the construction of Tallowa Dam, or represent a contribution driven by bank erosion along the Shoalhaven estuary qualitatively investigated in Chapter 4.

The fourth factor might be the volume added by shoreface supply to the beach (Source component E). Since direct field data on sediment resuspension and transport over the interface between the lower-shoreface and the nearshore are lacking, we can only indirectly estimate values for this contribution. If a relatively uniform rate of shoreline supply of 1-2 m^3/m/y is calculated for Seven Mile Beach-Comerong Island (Table 6.2), then an approximate volume of 700,000 to 1,400,000 m^3 would be available for beach accretion over the 41-year period.

The approximate value of 2,680,000 m^3 obtained using the shoreline displacement approach must be treated with caution, as considerable volumetric error might have been introduced by using the vegetation line for shoreline extraction as indicated in Chapter 6. Besides, the calculation of volume using the average of two profiles multiplied by the distance between them, provides only an approximate estimate. If the same methodology was applied for Culburra Beach for instance, a total accretion of approximately 240,000 m^3 would have occurred within the same time interval. However, it seems improbable that a closed tertiary level compartment like Culburra, that receives no fluvial contribution, with its budget derived from headland erosion (source contribution C in Figure 1.2), *in situ* production (source contribution D) and shoreface supply (source contribution E), can have received such a significant estimated input.

The sedimentary rocks (quartz-lithic siltstones from the Wandrawandian Formation) that form Crookhaven Heads and Penguin Head are relatively resistant to erosion, despite subaerial weathering observed on both headlands. Therefore, headland contribution (source contribution C) in terms of sediment input to the compartment can be considered negligible. Rock reefs, however, comprise 38 % (3.2 km^2) of Culburra's compartment area and serve as habitat for important carbonate-secreting organisms. *In situ* biogenic sediments (source component D) contribute significantly to the volume of sand in beach and nearshore sediments at Culburra, following the breakdown of their skeletons, as indicated by the carbonate content in the only beach (16.4 %) and nearshore (10.5 %) samples analysed in this tertiary level compartment. The beach sample (B14) was located in the middle of Culburra Beach and the nearshore sample (O29) approximately 1 km from the nearest rock reef. Thus, it is suspected that much higher carbonate content would be observed if samples closer to reefs and headlands were analysed.

There is not much detailed information and data for carbonate production by *in situ* organisms in temperate Australia as pointed out by James et al. (2013). However, a rough estimate can be done using carbonate production in similar temperate regions elsewhere. Carbonate production by a variety of coralline algae in macroalgal forests off southern California suggests values between 0.6 to 2 kg/m^2/y for varying water depths between 21 and 8 m, respectively (Round, 1981). Accretion rates by carbonate-secreting organisms including rhodophytes, cirripeds, molluscs, serpulids, bryozoans, vermetids and foraminiferans in water depths between 15 and 60 m in the Azores Archipelago were approximately 0.9 kg/m^2/y (Wisshak et al., 2010).

Using a value of 0.7 kg/m^2/y, carbonate-secreting organisms in the 3.2 km^2 of rock reefs within the tertiary level compartment of Culburra would produce approximately 2,240 tonnes of carbonate material per year, which is equivalent to 829 m^3/y (calcite density = 2711 kg/m^3). When multiplied by 41 years, carbonate production would be equivalent to approximately 34,000 m^3. This volume would increase to approximately 130,000 m^3 if adjacent 8.8 km^2 of rock reefs off Culburra (within the Shoalhaven coastal compartment) are considered

Due to the extension of rock reefs, a shoreface sediment supply to the beach (source component E) for the Culburra compartment over a decadal time scale, as suggested by Cowell et al. (2001) and Kinsela et al. (2016) for other parts of NSW, is unlikely to yield considerable amounts of sediment to the beach, unless the entire shoreface (down to 50 m depths) and not only the upper shoreface (down to 20 m depths; the seaward limit of the tertiary level compartments) is supplying sand. In this case, a limited shoreface supply of 0.5-1 m^3/m/y applied for Culburra would represent a contribution of approximately 75,000 to 150,000 m^3 over 41 years. The sum of this value with a possible *in situ* carbonate contribution would obtain close volumes to the 240,000 m^3 calculated using the shoreline displacement analysis, indicating that values for Culburra may not be far from reality.

The coastal budget for the southernmost tertiary level compartment of Warrain-Currarong is driven by fluvial input from Currarong and Coonemia creeks (source component A in Figure 1.2); erosion of Penguin Head, Kinghorn Point and Beecroft Peninsula (source component C); *in situ* production by the rock reefs carbonate organisms (source component D); estuarine deposition (sink component G) and exchange of material between Lake Wollumboola and the nearshore (component K); and shoreface supply to the beach (source component E).

It is possible that Currarong Creek provides fluvial sediment from its 12 km^2 catchment to the beach, as indicated by the southward transition in sediments from orange to brown colour (Figure 5.3), the decrease in sorting (Figure 5.1), the slightly higher feldspar content (Table 5.1) and the chemical weathering observed in some grains taken from sample B2 (Figure 5.4h), near Currarong. Conversely, its small estuary may also work as a sink of beach sediments as a flood-tide delta is observed on aerial images. Regardless of its sediment contribution or loss to the Warrain-Currarong compartment, the role of the Currarong Creek and its estuary seem negligible when compared to the role played by Lake Wollumboola, Coonemia Creek’s estuary.

Coonemia Creek has a catchment almost three times the size of the Currarong Creek catchment. However, before discharging into Warrain Beach, fluvial sediments from Coonemia Creek have to transit through Lake Wollumboola. This estuary is in its intermediate stage of evolution and acts as a trap for fluvial sediments (sink component G). Besides, no trace of fluvial sediment from the Coonemia Creek was observed on the adjacent beach and nearshore samples. Therefore contributions from this catchment to the Warrain-Currarong compartment (source component A) can be considered negligible too. In fact, landforms at Lake Wollumboola entrance indicate the lake is also a major sink of marine sediments for this tertiary level compartment. The rate or volume of sequestration, however, could not be determined by this study.

Using the shoreline displacement approach between 1972 and 2013 for Warrain-Currarong Beach, a volume of approximately 1,500,000 m^3 is obtained. This high accretional value for this embayment seems particularly exaggerated for a compartment that receives none or low fluvial sediment input and has reduced availability of sand in the shoreface. In fact, it is believed that a maximum of half (750,000 m^3) or even a third (500,000 m^3) of this estimated volume has been added to the system in the 41 year period. This suspicion is based on at least three facts: i) unlike Seven Mile Beach-Comerong Island, no seaward progradation was observed at Warrain-Currarong Beach during the same period; ii) reshaping of the the foredune and vegetation planting near WAR1 seemed to have ocurred before the 1987 image was taken, influencing considerably the profile with greatest displacement observed in this embayment; and iii) the shoreline was much closer in 1961 in respect to its position in 2013 (the baseline of the shoreline displacement analyses) than in 1972 at WAR2, indicating previous availability of material in the compartment. Besides these three facts, it was also observed during the monthly beach monitoring carried out between 2013 and 2015, that part of the coastal vegetation was buried by sand following strong onshore wind events, increasing the profile volume when compared to previous months. If the shoreline displacement was calculated using the dune vegetation for the same period, it would have shown a landward displacement of the vegetation boundary and therefore a reduction in the volume calculations. An opposite effect to what actually happened.

Fine to medium-grained sandstones of the Snapper Formation form the downsequence of Beecroft Peninsula, whereas quartz-lithic siltstones from the Wandrawandian Formation occur at Penguin Head and Kinghorn Point. These sedimentary rocks are relatively resistant to erosion although some can be observed or inferred from the pits and potholes of the Beecroft Peninsula, or the subaerial weathering occurring on all headlands. In either case, it seems reasonable to think that the size and rocky extension of Beecroft Peninsula may contribute significant amounts of sediment to the adjacent beach, as the limited area of the Coonemia catchment can not explain the transition in beach sediments that occur south of Hammerhead Point alone. Conversely, contributions from the much smaller headlands of Penguin Head and Kinghorn Point (source component C) can be considered insignificant.

It is also difficult to envisage a considerable shoreface sediment supply to the beach (source component E) for the Warrain-Currarong embayment over a decadal time scale unless the entire shoreface (down to 50 m depths) is supplying sand. In this case, a much wider area (59.6 km^2) than just the 16.8 km^2 of unconsolidated sediments in the upper shoreface has been providing sand to Warrain-Currarong Beach. In fact, 42 % (12.3 km^2) of the tertiary level compartment of Warrain-Currarong is composed of rock reefs limiting the amount of shoreface sand that would eventually end up on the beach.

The rock reefs, however, would represent an important source of *in situ* biogenic sediments (source component D) contributing significantly to the volume of sand, as indicated by the carbonate content in beach (32.6 %) and nearshore (26.4 %) samples observed near Currarong. Using the same production estimation for Culburra (0.7 $kg/m^2/y$), carbonate-secreting organisms in the 12.3 km^2 of the rock reefs within the tertiary level compartment of Warrain-Currarong would produce approximately

8,610 tonnes of carbonate material per year, which is equivalent to 3,186 m^3/y (calcite density = 2711 kg/m^3). When multiplied by 41 years, carbonate production would be equivalent to approximately 130,000 m^3. This volume would increase to approximately 590,000 m^3 (14,400 m^3/y) if adjacent 43.4 km^2 of rock reefs off Warrain-Currarong (within the Shoalhaven coastal compartment) are considered.

7.2 Recommendations

This study addressed the sediment budget of the Shoalhaven coastal compartment. A sector of the coast composed of three very distinct beaches separated by headlands. Each of these beaches was considered a different tertiary level compartment. Sources, sinks and sediment transport pathways were investigated in a logical sequence from catchment to the nearshore, whereas individual volumetric contributions and losses were estimated for each component of the sediment budget and compared to the changes observed on each beach over approximately four decades using a shoreline displacement analysis based on aerial photography.

The Seven Mile Beach-Comerong Island tertiary level compartment was the most studied of the three sectors. The focus on the northernmost compartment is clear when comparisons involving the amount of analyses dedicated to each tertiary level compartment are made. The Seven Mile Beach-Comerong Island tertiary level compartment is where the Shoalhaven River, the most important geographical feature of the study area, discharges into the Tasman Sea. Nevertheless, this study investigated all tertiary level compartments within a secondary level compartment defined by Geoscience Australia. The national agency for geoscience research and geospatial information coordinated the development of a nationally-consistent, process-based multi-scale hierarchical coastal classification for the entire country that resulted in more than 350 secondary level compartments (McPherson et al., 2015).

Another strength of this study is related to the its links to NSW coastal policy. During the final stages of this thesis, the Coastal Management Bill 2016 (NSW Legislative Council, 2016) was introduced into NSW Parliament, as part of the coastal reforms. The objectives of the proposal for the Coastal Management Act 2016 are to manage the coastal environment in a manner to mitigate current and future risks from coastal hazards, among other particular aims, recognizing the local and regional scale effects of coastal processes, and the dynamic nature of the shoreline. The Bill subdivides the NSW state into 46 sediment compartments and also recognises the fact that the beach zone fluctuates as the coastline or estuarine foreshore experiences net long-term recession or accretion due to changes in the sediment budget.

There are constraints on the extent to which a budget of sediments can be effectively estimated, as there will always exist uncertainties associated with the volumes, processes and exchanges that need to be recognized by those using such estimates as pointed out by Walton et al. (2012). Certain errors and limitations in accuracy are expected in every measurement (Kraus and Rosati, 1998), as direct measurements of many quantities cannot be made.

Notwithstanding these limitations, the coastal budget presented here showed how the concept of conservation of mass can be directly applied to the littoral sediments of the Shoalhaven Coast. Several assumptions and uncertainties constrain the final coastal budget, but this study provides the framework for future research, offering a broad view of the coastal area by organizing what is known and identifying where gaps in understanding exist. It also provides an avenue for management action using not only the results presented in this study but also enabling further modelling to explore scenarios of erosion or accretion in response to natural events or engineering interventions in the area.

Based on the results of this thesis, the data availability and the current limitations of this project, several scientific and management recommendations are made and listed below. These recommendations are mostly intended to improve several gaps raised in the coastal budget section of this chapter and identified by question marks (?) in the summary of the budget presented in Figure 7.2. Apart from those gaps of information, some recommendations are made in order to improve the confidence level and reduce uncertainties in the estimation of volumes.

"The main challenge in developing a budget of sediments is to accurately assess the contributions and losses". This quote by Komar (1998) provides the foundation for a budget of a coastal compartment whose most important feature, in the case of the Shoalhaven coastal compartment, is the Shoalhaven River.

Rivers are by far the most important suppliers of sediment to the coast (Davies, 1974) with much of the contribution of large rivers sequestered in subsiding deltas, as rivers discharge to passive margins and marginal seas (Milliman and Syvitski, 1992). In

NSW, coastal catchments are relatively small due to the Great Dividing Range, the longest complex of mountains in Australia, whereas the rainfall regime is low with marked decreases towards south and west. Evidence suggests that very few rivers are supplying significant amount of sediments to the coastline directly in eastern Australia, it appears that those whose estuaries, in mature stage of infill and with reduced tidal prism, are more capable of delivering sediments to the coast at times of high discharge, as pointed out by Davies (1974).

In this study, no volumetric estimation was possible for the other catchments that discharge into the tertiary level compartments, especially Currarong Creek. Quantification of fluvial yield on this catchment would have to be calculated in order to improve current understanding of delivery of sediments to Currarong Beach and the budget of the southernmost tertiary level compartment.

There are eight real time gauges currently measuring water level and discharge in the Shoalhaven catchment but only two of those, located in the upper catchment (stations 215002 at Warri and 215008 at Kadoona), are installed in the main stream of the river. A downstream gauge (station 215430 at Grady's Caravan Park) located at Burrier, close to the tidal limit, started in 2013, but lacks discharge data. Whereas sediment load can be indirectly calculated using daily discharge, a lot of uncertainties and margin for errors remain, especially when suspended sediment concentration measurements are missing.

The sediment yields calculated for the catchment in this study were mainly derived from the volumetric difference of sediments deposited at Lake Yarrunga over the years and based on limited bathymetric data during the 2014 campaign. Therefore, there is a paramount need to improve these calculations and if possible to determine the quantities of bedload and suspended sediment yields especially immediately upstream of the estuary. Despite not as straight forward as the bed material sampling collected for this thesis, the former can be done by using a Helley-Smith bedload sampler and the latter by a point-integrating sampler or derived from turbidity meters, over a variety of flow conditions. Studies of sediment yield still remain the most serious deficiency in monitoring programs of water authorities throughout Australia, as pointed out by Hean and Nanson (1987), about 30 years ago.

There is also a need to repeat a complete bathymetric survey of the Shoalhaven estuary to improve the volumetric calculations. The 2006 survey, completed 10 years ago, was very dense, well executed, and covered the whole estuary from Burrier to both entrances, including areas in the Crookhaven estuary, Curleys Bay, Broughton Creek and other minor channels. The recommended new survey does not need to cover all these areas but should cover the area presented in Figure 4.3 and Figure 4.4, or even extend further upstream towards Burrier if shallow water is not a constraint. The idea behind a new complete survey is that the changes in the middle and upper estuary can be better understood as opposed to the 2015 survey which only covered the lower estuary between the entrances, and there is no other survey taken upstream of the Long Reach to compare with the 2006 survey.

A less intensive bathymetric campaign that can be done in two or three days, is recommended around Shoalhaven Heads, covering not less than the estuarine area surveyed in 1989 (Figure 4.4), so that comparisons of sediment deposition and return after a breaching event can be made. In this study, it was possible to calculate a loss of approximately 160,000 m^3 from 1981 to 1989, due to a breaching event that happened in 1988. However, this figure could be much higher if the volume that accumulated during the 1980's and preceded the opening of the entrance was known. In this sense, it is suggested that this area be surveyed not only after flood events as happened in 1981 and 1989, but during times when the entrance is closed to better assess the amount of sediment that returns from the nearshore. Once this return is more completely understood, better decisions regarding the mechanical opening of Shoalhaven Heads, a local community concern, and prediction of shoreline behaviour based on the net input to the nearshore, can be made.

A second bathymetric survey of Lake Wollumboola would allow comparisons with the 1991 survey to be made. The volumetric difference between these surveys would help to understand the sink role played by the lake in the sequestration of adjacent beach and nearshore sediments.

Regarding the nearshore, it is highly recommended to have the area adjacent to Shoalhaven Heads surveyed not only following breaching events but also when the entrance is closed so that a better idea of the total volume is obtained. This campaign must be coupled with the Shoalhaven estuary survey and can be technically done in two days maximum by professional surveyors and cover the whole depositional bar seaward to the 20 m contour line, an area similar to the survey conducted in 1989 (Figure 6.5). A survey down to the 20 m contour line would allow most of the large volume of sediment deposited in the nearshore be calculated. In this thesis, nearshore data from 1981, 1989, 2006 and 2012 were used to calculate the contributions to the coast. However, a much more precise volume could be calculated if another survey in the 1980's, or after the closing of Shoalhaven Heads in 1994 had been taken.

It is necessary to understand the role and estimate the shoreface supply of sands to the beach not only in the past 7,000 years but especially nowadays. A lot of coastal research has focused on beach response and bar movement on sub-decadal time scales, but very little is known about the sediment exchanges between the upper and lower shoreface, the consequent shoreline responses over decadal time scales (Cowell et al., 2001), the current rate of sand supply to different beaches, or the response of shoreface supply to sea-level rise. Data on sediment suspension and flux over the shoreface collected in the field are lacking in southeastern Australia (Wright, 1995). If subtle rates (1-2 m^3/m/y) of shoreface sand supply persist on some southeast Australian beaches, as indicated by Kinsela et al. (2016), it is extremely important to be able to estimate those rates, to a degree of confidence that would assist coastal managers to make better decisions over the long term (decades).

During the course of this thesis, two other surveys conducted by the NSW's Office of Environment and Heritage were kindly provided for use in this thesis, a nearshore survey conducted in 2013 and a more recent estuarine to nearshore survey done in 2015 following the breaching of Shoalhaven Heads. Despite the merits of obtaining these data in a logistically difficult and challenging situation of having to cross the surf zone and channel formed when Shoalhaven Heads was open, as well as, the advances in technology with the use of Terrestrial Laser Scanner and Jet Ski assisted bathymetry, the survey extents did not coincide sufficiently to compare previous surveys. So, it is highly recommended that the next bathymetric surveys cover the estuarine and nearshore area previously surveyed.

A collection of current/wave data using an ADCP coupled with wave gauge in the nearshore of Seven Mile Beach-Comerong Island over the course of two consecutive tidal cycles both during neap and spring tides is recommended. Whereas there are data to calibrate a hydrodynamic model of the Shoalhaven estuary, the absence of nearshore data restricts the model domains to the estuarine limits. A bottom mounted, upwards facing current profiler and a wave directional system would allow the model to be extended to the nearshore, improving considerably the understanding of several coastal processes in the area.

Estimation of sediment volume, transport pathways and headland bypassing could be considerably improved in future with acquisition of detailed bathymetry or interferometric sidescan sonar over the entire nearshore-shoreface area (down to 50 m depth) or at least around Crookhaven Heads and between Penguin Point and Hammerhead Point. A detailed map off Crookhaven Heads would light shed on the possible leak of sediments from Culburra to Seven Mile Beach-Comerong Island, whereas the survey south of Penguin Point would fill uncharted gaps, covering the extent of the rock reefs in the area and refine information regarding sediment availability in the nearshore in the Warrain-Currarong embayment.

Important knowledge would be obviously gained if all offshore areas of the Shoalhaven coastal compartment are mapped as suggested above. This would allow not only detailed mapping of the rock reefs but also better understanding of the areal extension versus depth, so important for estimations of carbonate production by organisms. This component of the budget would also be benefited if population density and abundance of carbonate-secreting organisms were assessed.

The continuation of the monitoring of the beach berm at Shoalhaven Heads is also recommended. Council has been monitoring the entrance and maintaining the dry notch, a 50 m wide incision at a height of 2 m AHD that ensure that sand entrance opening is fast, for several years now and it is suggested that the monitoring continue to cover at least the area of Figure 5.22, and possibly expand the survey a bit further to the north and south to improve calculations of volume exchanged in case of a larger breaching occurs.

It is also recommended that the beach monitoring program be continued. The profile locations at Seven Mile Beach-Comerong Island were inherited from initial data collected by researchers at University of New South Wales, and during this thesis, the monitoring was expanded to the other two beaches (Culburra and Warrain-Currarong) to provide an understanding of their individual behaviour, at first and then draw comparison in terms of any potential synchronous regional response over time. However, two years of monitoring are insufficient to detect long term trends and therefore, it would be wise to continue the monitoring for several more years, and possibly reduce the monitoring interval to bimonthly (6 per year). It takes two days (two low tides) to monitor the 10 profiles at the three beaches with a RTK-GPS.

It is also desirable an assessment of *in situ* carbonate production by marine organisms as their contributions to individual beach and nearshore surficial sediment samples accounted for more than 30 % and 25 % of the total sediments near Currarong, respectively.

It is highly recommended to maintain the dry notch at Shoalhaven Heads and the mechanical opening of the entrance during flood events to reduce inundation, when the water level inside the estuary is higher than on the beach, and even to review the current opening trigger value, as it appears that it was not able to prevent the high water levels and inundation of 2013 and 2015 that flooded parts of Shoalhaven Heads community.

The mechanical opening of the entrance using a bulldozer appears to be a relatively simple and cost-effective mechanism to alleviate damage caused by floods. However, the entrance remained open for a maximum period of 9 months following the 4 times the artificial opening procedures were put in practice in the last 18 years. Whereas the closing regime is determined by the variability of the river flow, it seems that the deposition process occurring along the Shoalhaven channel, downstream of the bifurcation with Berrys Canal, is hindering the flow's ability to keep the entrance open for longer periods, by shallowing its bed and slowing the flow. Within time, this area tends to become a backwater, especially as the alternative course of the river, via Berrys Canal continues to evolve and divert more water. Despite concerns associated with dredging activities and large volume transported by trucks, it would be useful to investigate the feasibility of deepening and widening the Shoalhaven Heads channel, especially whether removing the shoals that are constricting the channel to the southeast of Old Man Island would increase flow.

Regarding Shoalhaven Heads itself, it seems that dredging the adjacent estuarine shoals is not a feasible option due to the volumes that are deposited there, the natural morphodynamics of the entrance subject to high energy wave action, and community concerns. Other solutions may be sought if the local community wants to get rid of the sediment deposit there, such as increasing the flow to the area, as described in the previous paragraph or looking into sand pumping options, for instance.

The vegetation development at Shoalhaven Heads entrance is of concern in relation to the width of the breached channel, and therefore, the volume exchanged in both ways between the estuary and nearshore. It was noticed that from 1949 to 2015, vegetation expanded and colonized most of the beach berm, including forming a vegetated island covered with high shrubs and trees to the north of the dry notch, and that during the recent mechanical openings the channel width was confined by the established vegetation on both sides of the channel. It is worth to further investigate what effects the removal of the nearby vegetation would have on sediment exchange and entrance dynamics, considering the potentially adverse consequence for the Shoalhaven Heads SLSC, and the return of sand to the estuary when the entrance is closing.

At Berrys Canal, the system is still adjusting as bank erosion and scouring were observed in this study. One way that could lead to substantial inhibition of the erosion would be reducing the flow through Berrys Canal by increasing the flow via the Shoalhaven Heads channel. This option would possibly include the shoal removal constricting the channel near Old Man Island discussed before and probably an effort to artificially intervene opening Shoalhaven Heads entrance more often, when estuarine water level is high but lower than necessary for flood-triggered operation.

Regarding beach management, the three beaches respond differently to the offshore wave climate conditions, as one would expect from beaches with different length, orientation and sediment texture, especially when nearshore wave characteristics are so different due to wave refraction at Beecroft Peninsula and Sir John Young Banks. Severe erosion due to major storms tends to affect the beaches in different ways but losses are magnified when storms coincide with elevated water levels, such as king tides.

At Seven Mile Beach-Comerong Island, riverine sediments continue to be delivered to the coast and there is a tendency for the beach to increase in volume over the medium (decadal) time scale, despite the significant decrease in sediment yield to the estuary after the construction of Tallowa Dam. There are also sediments remaining from previous breaching events deposited in the nearshore adjacent to Shoalhaven Heads that would eventually be transported to shallow water and redistributed alongshore. Thus, Seven Mile Beach-Comerong Island accretion is likely to continue even if no more breaching and input of sediment happens in the next few years.

However, changes in morphology and volume over sub-decadal time scales, reflecting the natural variability, are expected.

Over the past decades, the northern end of Seven Mile Beach, between SH1 and SH2 has prograded and accumulated more sand than Shoalhaven Heads and Comerong Island monitored areas (Figure 7.3), consistent with the greater rate of incipient foredune accretion reported at the northen end of the beach by Wright (1970) and indicating that this pattern is likely to continue in the future. The beach adjacent to Shoalhaven Heads SLSC (SH3) has regained the sand lost during the 1970's storms. However, seawards displacement only increased a few meters in relation to its position in 1949, and therefore, removal of sand adjacent is not recommended, in order to protect its integrity in case a similar storm or a series of storms occur. Furthermore, scarping is likely to occur both north and south of the river mouth at Shoalhaven Heads following breaching events, as a natural mechanism to rebuild the beach across the entrance.

At Culburra Beach, the situation is much different to that at Seven Mile Beach-Comerong Island, as there is no catchment source, the shoreface accretion wedge is poorly developed or absent and not much sand exists in the nearshore, and beach front houses and infrastructure are distributed along much of the foredune. A net seaward shoreline displacement has been observed over the past 65 years with relatively minor impact by storms to both north and south ends. However, at the middle of the embayment, a major recession happened as a result of the 1970's storms and the shoreline reached its pre-storm position only recently, with the build up of an incipient foredune of approximately 3.5 m in height, that decreases towards the southern end. Backing the incipient foredune, a much higher established foredune (dune ridge with intermediate plant species developed from incipient foredune) exists with houses encroaching onto it. In case a strong storm or a series of storms occur, resulting in similar threats to the one posed during the 1970's, parts of the foredune may experience erosion with considerable consequences involving property loss. At the southern end houses are very close to shore and the foredune is smaller making property loss more susceptible in case of severe erosion. Therefore, future development along the embayment should be carefully planned and site specific for the properties located near the foredune escarpment.

No management action is required at Warrain. The beach has accreted considerably and sand volume increased since the 1950's. The gained sand is desirable to protect the SLSC and two of the houses that are close to the shoreline, because the waves are much higher in the north than in the south of the embayment. At Currarong, on the other hand, evident foredune collapse was observed along the beach, despite no further recession observed during the 2013-2015 monitoring and the low energy wave climate. The continuity or expansion (with Terrestrial Laser Scanner) of the beach monitoring here is highly recommended and actions to mitigate the erosion and protect the road must be taken only if recession continues in the future.

7.3 Conclusions

The closed Shoalhaven coastal compartment is composed of three tertiary level compartments separated by the headlands of Crookhaven Heads and Penguin Head that impose obstacles to the exchange of sediments between Seven Mile Beach-Comerong Island, Culburra and Warrain-Currarong beaches. Only during extreme storm conditions, when the Shoalhaven River is in flood and Shoalhaven Heads is breached, is sediment, especially fine material, lost from the system, escaping the Shoalhaven coastal compartment to deeper waters of the continental shelf and also bypassing the headlands of Black Head and Beecroft Peninsula. When this happens, it seems that the plume of sediments spares the tertiary compartments to the south of Crookhaven Heads.

The main sources of sediment to the budget of the northernmost tertiary level compartment come from the Shoalhaven catchment and Shoalhaven estuary erosion, whereas estuarine deposition and mining are considered the main sinks. A secondary role of contribution, roughly estimated in this study, may be credited to long term shoreface supply to the beach. Erosion of headlands, *in situ* production, aeolian loss and the Crooked River catchment and estuary are considered to have a minor role.

Approximately 2,150,000 m^3 of fluvial sediments from the Shoalhaven River were delivered to the Shoalhaven estuary between 1981 and 2006. In the 25-year period, the estuary experienced a net accretion of approximately 1,020,000 m^3, and at least 1,065,000 m^3 of sediment was deposited in the nearshore area between Shoalhaven Heads and Crookhaven Heads. The estuarine balance showed that the estimated volume deposited by the river was approximately equivalent to the volume deposited in the estuary plus the material delivered to the nearshore.

The budget of the northernmost tertiary level compartment was balanced using the values transferred to the nearshore and the volumetric change experienced at Seven Mile Beach-Comerong Island between 1972 and 2013. It was calculated an accretion of approximately 2,680,000 m^3 of sediments obtained using the shoreline displacement in the 41-year period. A residual of 1,615,000 m^3 was obtained when compared to the calculated nearshore deposition between 1981 and 2006.

It was suggested that the bulk of the residual would have been added to the nearshore before 1981, transported from the breaching deposit towards the beach after 2006, supplied from the shoreface to the beach in the past four decades and/or that more fluvial/estuarine sediments were discharged to the nearshore between 1981 and 2006.

Culburra Beach received no sediment from fluvial sources and the beach accreted approximately 240,000 m^3 between 1972 and 2013. It is estimated that most of the contributions derived from *in situ* carbonate-secreting organisms and a limited shoreface supply of sand to the beach.

A volume of approximately 1,500,000 m^3 was obtained using the shoreline displacement approach during the same time interval for the Warrain-Currarong Beach tertiary level compartment, although it appears to have been over-estimated. The southernmost compartment received none or negligible fluvial sediments from Coonemia Creek and possibly low volumes from Currarong Creek. Landforms at the entrance of Lake Wollumboola, a shallow saline coastal lagoon, suggests that the lake is a major sink of marine sediments for this compartment. Likewise Culburra, It is estimated that most of the contributions derived from *in situ* carbonate-secreting organisms and a limited shoreface supply.

Data limitation and uncertainties constrained the modelled budget, but did not deter the application of the methodology. Scientific and management recommendations such as the continuation of the beach monitoring and improvements in the bathymetric survey coverage, among others, were made in order to refine the budget in future efforts.

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Appendix 1- Historical archive of aerial photographs

This Appendix tabulates the aerial photography between 1949 and 2014 used in this thesis.

Table A1.1 Historical archive of aerial photographs

Date	Scale	Run	Photos	Institution
02/12/1948	-	-	-	-
04/04/1949	25,000	3	5142, 5144, 5145	LIC
21/09/1961	-	1N	5040- 5046	LIC
21/09/1961	-	2N	5017-5025	LIC
21/09/1961	-	3N	5005- 5013	LIC
21/09/1961	-	4N	5080-5088	LIC
21/09/1961	-	5N	5072-5076	LIC
21/09/1961	-	6N	5051	LIC
??/08/1963	-	6K	5182, 5184, 5186	LIC
16/04/1970	-	-	-	AWACS
23/05/1970	-	4	5150	LIC
23/05/1970	-	3	5111	LIC
01/07/1972	-	11	5092-5099, 5101-5106	LIC
01/07/1972	-	11A	5090,5091	LIC
01/07/1972	-	12	5072	LIC
29/12/1974	-	6	24, 26, 28	LIC
29/12/1974	-	7	12, 14	LIC
28/07/1977	-	-	-	-
23/08/1977	-	-	-	AWACS
26/11/1977	-	-	45, 47, 57, 59, 63, 78, 80	-
10/07/1978	-	-	-	-
28/07/1978	-	-	-	-
26/06/1979	-	-	-	AWACS
28/02/1980	-	-	-	AWACS
12/02/1981	-	-	-	LIC
27/06/0981	25,000	59B	126	LIC
28/06/1981	25,000	60	72	LIC
28/06/1981	25,000	61	101-113	LIC
28/06/1981	25,000	62	43-49	LIC
28/06/1981	25,000	63	28, 30 34, 36, 38	LIC
09/01/1982	15,000	D	-	-
19/07/1983	-	5	327, 331	-
26/04/1984	-	-	-	-
13/05/1984	-	-	-	ASO
27/09/1984	-	10	890	ASO
01/08/1986	25,000	63	42-44	LIC
08/07/1987	12,000	-	66, 68	NSW Govt.
02/10/1987	40,000	1	22	LIC
06/04/1989	-	-	-	AWACS
22/04/1991	-	-	-	AWACS
19/01/1993	25,000	8	03-13	LIC
04/02/1993	25,000	10	178-187	LIC
04/02/1993	25,000	12	189-197	LIC
22/02/1993	25,000	1	111	LIC
22/02/1993	25,000	9	65-75	LIC

Date	Scale	Run	Photos	Institution
22/02/1993	25,000	13	101-105	LIC
15/01/1996	-	-	-	Air Maps Aus.
15/04/2001	12,000	16	65-71	LIC
15/04/2001	12,000	17	74-78	LIC
15/04/2001	12,000	18	82	LIC
17/04/2001	12,000	12	20-26	LIC
17/04/2001	12,000	15	55-59	LIC
28/01/2002	25,000	11	87-97	LPI
28/01/2002	25,000	12	146-158	LPI
28/01/2002	25,000	61	101-113	LPI
22/03/2002	25,000	1	03	LPI
24/03/2002	25,000	8	139-149	LPI
24/03/2002	25,000	10	78-89	LPI
09/04/2002	25,000	13	-	LPI
19/01/2005	12,000	14	222-226	LIC
2008	-	ADS40	Moss Vale	LPI
2009	-	ADS40	Kiama, Jervis Bay	LPI
2013-2014	-	ADS40	Kiama, Jervis Bay	LPI

Appendix 2- Historical archive of Landsat imagery

This appendix tabulates the Landsat imagery from 1972 to 2016 used in this thesis.

Table A2.1 Historical archive of Landsat imagery

Satellite	Date	Sensor	Resolution	Satellite	Date	Sensor	Resolution
L1	05/11/1972	MSS	60	L5	09/06/1997	TM	30
L2	12/10/1975	MSS	60	L5	16/09/1998	TM	30
L2	21/09/1979	MSS	60	L5	27/10/1998	TM	30
L2	10/08/1980	MSS	60	L5	21/12/1998	TM	30
L2	28/08/1980	MSS	60	L5	06/01/1999	TM	30
L2	15/09/1980	MSS	60	L5	16/02/1999	TM	30
L2	28/09/1981	MSS	60	L5	12/04/1999	TM	30
L2	03/11/1981	MSS	60	L7	18/07/1999	ETM+	15
L5	16/07/1987	TM	30	L7	10/08/1999	ETM+	15
L5	02/09/1987	TM	30	L5	12/09/1999	TM	30
L5	18/09/1987	TM	30	L5	19/09/1999	TM	30
L5	04/10/1987	TM	30	L5	06/11/1999	TM	30
L5	08/01/1988	TM	30	L5	22/11/1999	TM	30
L5	24/01/1988	TM	30	L7	30/11/1999	ETM+	15
L5	25/02/1988	TM	30	L7	02/02/2000	ETM+	15
L5	12/03/1988	TM	30	L7	27/07/2000	ETM+	15
L5	28/03/1988	TM	30	L7	13/09/2000	ETM+	15
L5	13/04/1988	TM	30	L7	25/11/2000	ETM+	15
L5	18/07/1988	TM	30	L7	15/04/2001	ETM+	15
L5	03/08/1988	TM	30	L7	11/05/2001	ETM+	15
L5	04/09/1988	TM	30	L7	27/05/2001	ETM+	15
L5	20/09/1988	TM	30	L7	28/06/2001	ETM+	15
L5	06/10/1988	TM	30	L7	19/09/2002	ETM+	15
L5	22/10/1988	TM	30	L7	05/10/2002	ETM+	15
L5	07/11/1988	TM	30	L7	06/11/2002	ETM+	15
L5	23/11/1988	TM	30	L7	25/01/2003	ETM+	15
L5	09/12/1988	TM	30	L7	15/04/2003	ETM+	15
L5	10/01/1989	TM	30	L7	20/07/2003	ETM+	15
L5	27/02/1989	TM	30	L7	12/01/2004	ETM+	15
L5	06/08/1989	TM	30	L7	04/06/2004	ETM+	15
L5	23/09/1989	TM	30	L7	22/05/2005	ETM+	15
L5	02/03/1990	TM	30	L7	28/07/2006	ETM+	15
L5	24/07/1990	TM	30	L7	04/01/2007	ETM+	15
L5	09/08/1990	TM	30	L7	19/10/2007	ETM+	15
L5	25/08/1990	TM	30	L7	23/01/2008	ETM+	15
L5	10/09/1990	TM	30	L8	18/04/2013	OLI	15
L5	26/09/1990	TM	30	L8	20/05/2013	OLI	15
L5	28/10/1990	TM	30	L8	15/01/2014	OLI	15
L5	05/03/1991	TM	30	L8	04/03/2014	OLI	15
L5	21/03/1991	TM	30	L8	29/03/2014	OLI	15
L5	22/04/1991	TM	30	L8	07/05/2014	OLI	15
L5	25/06/1991	TM	30	L8	17/06/2014	OLI	15
L5	27/07/1991	TM	30	L8	04/08/2014	OLI	15
L5	12/08/1991	TM	30	L8	28/09/2014	OLI	15
L5	28/08/1991	TM	30	L8	01/12/2014	OLI	15

Satellite	Date	Sensor	Resolution	Satellite	Date	Sensor	Resolution
L5	29/09/1991	TM	30	L8	24/04/2015	OLI	15
L5	02/12/1991	TM	30	L8	19/05/2015	OLI	15
L5	18/12/1991	TM	30	L8	13/07/2015	OLI	15
L5	19/01/1992	TM	30	L8	07/08/2015	OLI	15
L5	26/05/1992	TM	30	L8	30/08/2015	OLI	15
L5	13/07/1992	TM	30	L8	08/09/2015	OLI	15
L5	08/01/1994	TM	30	L8	01/10/2015	OLI	15
L5	24/01/1994	TM	30	L8	10/10/2015	OLI	15
L5	30/04/1994	TM	30	L8	04/12/2015	OLI	15
L5	04/08/1994	TM	30	L8	13/12/2015	OLI	15
L5	21/09/1994	TM	30	L8	29/12/2015	OLI	15
L5	30/11/1994	TM	30	L8	30/01/2016	OLI	15
L5	11/01/1995	TM	30	L8	06/02/2016	OLI	15
L5	01/04/1995	TM	30	L8	22/02/2016	OLI	15
L5	17/04/1995	TM	30	L8	02/03/2016	OLI	15
L5	04/06/1995	TM	30	L8	18/03/2016	OLI	15
L5	07/08/1995	TM	30	L8	25/03/2016	OLI	15

Appendix 3- Sediment properties

This appendix tabulates the coordinates and results of the grain size analyses for the estuarine, beach and offshore samples using the logarithmic Folk and Ward (1957) graphical measures.

Table A3.1 Sediment sample location and grain size results

Sample	X	Y	Mean Size	Sorting	Skewness	Kurtosis
E1	268484	6136504	-0.38	1.07	0.19	2.77
E2	268474	6136558	1.90	1.13	0.09	1.03
E3	269261	6136707	-0.14	0.60	0.22	0.81
E4	269237	6136763	0.47	0.82	0.01	1.16
E5	270058	6137001	-0.03	0.89	0.10	1.06
E6	270073	6136933	0.39	0.91	0.05	0.96
E7	270827	6136822	3.62	1.98	0.26	1.28
E8	270764	6136814	1.31	1.21	0.18	1.23
E9	271050	6135842	0.92	0.86	0.05	1.06
E10	271018	6135802	0.41	1.09	0.20	1.10
E11	272160	6135567	1.70	1.66	0.26	0.91
E12	272208	6135496	-0.04	0.67	0.18	0.79
E13	272785	6136397	0.89	1.04	0.25	1.38
E14	272824	6136365	0.51	0.89	0.02	1.00
E15	273437	6137065	2.06	1.37	0.32	1.74
E16	273366	6137035	2.65	1.90	0.09	0.97
E17	272636	6137323	0.39	0.96	0.04	0.97
E18	272636	6137230	1.09	0.82	0.10	1.03
E19	271691	6137570	-0.20	1.51	0.19	1.17
E20	271659	6137506	0.73	0.78	0.06	1.00
E21	270918	6138275	0.92	1.68	0.34	1.05
E22	270990	6138291	0.27	0.81	0.04	0.98
E23	271525	6139122	0.46	0.77	-0.01	1.18
E24	271558	6139089	1.75	0.95	0.23	1.37
E25	272394	6139264	1.33	0.71	-0.06	1.30
E26	272370	6139351	0.59	0.93	-0.02	0.93
E27	273390	6139781	0.32	0.79	-0.02	1.02
E28	273421	6139678	1.92	0.91	0.26	1.22
E29	274383	6140097	1.00	0.94	0.10	1.14
E30	274351	6140185	0.32	0.79	-0.01	0.99
E31	275527	6140701	1.05	0.76	-0.01	0.89
E32	275543	6140599	1.57	0.63	0.07	1.38
E33	276508	6140599	0.90	1.04	0.25	1.36
E34	276464	6140549	1.72	0.74	0.10	1.14
E35	276533	6139950	0.47	1.51	-0.17	1.28
E36	276432	6139950	2.76	1.95	0.51	1.44

Sample	X	Y	Mean Size	Sorting	Skewness	Kurtosis
E37	275961	6139355	2.89	1.71	0.44	1.09
E38	275981	6139297	0.24	1.07	0.34	1.24
E39	274838	6139054	4.05	2.42	-0.05	0.78
E40	274940	6139027	0.91	0.84	0.13	1.08
E41	275343	6138607	5.96	1.36	0.12	0.97
E42	275335	6138693	1.86	1.18	0.30	1.60
E43	276290	6139017	1.10	0.80	0.11	1.07
E44	276309	6138900	1.91	1.25	0.13	1.69
E45	277178	6138759	2.83	1.62	0.32	1.05
E46	277127	6138690	1.53	1.43	0.33	1.46
E47	277993	6138202	3.88	2.10	0.45	0.87
E48	277958	6138272	2.02	1.62	0.43	1.88
E49	278396	6139215	0.39	1.16	0.30	1.17
E50	278391	6139347	2.16	1.44	0.44	1.60
E51	279175	6138856	0.09	0.85	0.19	0.88
E52	279105	6138750	2.29	1.44	0.41	1.53
E53	280004	6138822	5.97	1.45	0.09	0.95
E54	279953	6138869	3.25	2.51	-0.02	0.87
E55	280839	6139510	1.37	1.09	0.21	1.24
E56	280861	6139366	0.02	0.86	0.34	0.95
E57	281673	6139898	1.10	0.75	-0.01	0.87
E58	281703	6139678	0.95	0.95	0.02	1.04
E59	281722	6139494	1.11	0.95	-0.03	1.03
E60	282471	6140473	0.49	0.83	0.01	1.09
E61	282501	6140311	4.55	2.22	-0.05	0.87
E62	282563	6139616	3.89	1.92	0.42	1.09
E63	282567	6139517	4.62	2.39	-0.08	0.83
E64	283466	6140619	0.28	1.70	0.33	1.97
E65	283473	6140519	3.54	2.29	0.35	0.81
E66	283592	6139739	2.60	2.77	0.44	0.73
E67	283602	6139656	0.24	0.84	0.09	0.90
E68	284677	6140616	0.94	0.99	0.17	1.33
E69	284700	6140461	1.59	0.69	0.08	1.33
E70	284713	6140339	1.94	1.82	0.52	1.63
E71	285375	6140771	1.74	1.66	0.36	1.29
E72	285421	6140456	1.62	1.44	0.38	2.06
E73	285398	6140605	0.79	1.17	-0.15	0.86
E74	286512	6140810	1.39	0.71	-0.06	1.28
E75	286430	6140364	2.07	1.82	0.34	1.01
E76	286463	6140572	2.29	1.62	0.54	1.76
E77	287455	6140599	1.34	0.77	-0.02	1.10
E78	287425	6140447	2.84	1.98	0.31	0.85
E79	287333	6139937	1.40	1.17	0.25	1.77
E80	288272	6140031	1.41	1.09	0.22	1.49
E81	288176	6139849	2.20	1.12	0.22	1.64

Sample	X	Y	Mean Size	Sorting	Skewness	Kurtosis
E82	288131	6139745	2.04	1.08	0.28	1.49
E83	289148	6139484	1.16	1.20	0.25	1.67
E84	289066	6139325	1.30	1.45	0.26	1.71
E85	288999	6139143	3.87	1.92	0.24	1.09
E86	290036	6138844	1.55	0.87	0.04	1.08
E87	290150	6139054	1.06	1.51	0.35	2.22
E88	290035	6138615	2.33	2.10	0.55	1.75
E89	290773	6138174	1.95	1.68	0.38	1.51
E90	290862	6138435	1.89	0.80	-0.06	0.93
E91	290961	6138637	1.37	1.72	0.41	2.02
E92	291398	6138566	1.46	1.63	0.40	2.06
E93	291426	6138286	1.10	0.89	0.07	1.01
E94	291433	6137998	1.28	0.73	-0.07	1.08
E95	291523	6137711	1.53	0.85	0.02	1.10
E96	291986	6138383	3.80	2.00	0.27	0.99
E97	291862	6138491	2.26	1.73	0.42	1.70
E98	291751	6138668	1.71	1.64	0.37	1.86
E99	292387	6139021	3.06	2.42	0.46	0.87
E100	292264	6139048	4.56	1.98	0.07	1.00
E101	292105	6139145	3.38	2.27	0.35	0.99
E102	292710	6139944	4.46	2.08	-0.01	0.90
E103	292737	6139805	3.38	2.11	0.51	0.96
E104	292778	6139685	3.03	2.29	0.50	1.16
E105	293625	6140336	1.86	0.98	0.11	1.07
E106	293666	6140117	1.81	0.66	0.12	0.90
E107	293534	6139881	2.00	0.71	0.02	0.80
E108	293522	6140600	1.49	0.83	0.04	1.21
E109	290988	6137447	1.21	0.61	-0.24	0.88
E110	291083	6137411	1.55	0.85	0.02	1.11
E111	291372	6136713	1.91	0.62	0.13	0.76
E112	291306	6136623	1.08	0.78	-0.08	0.93
E113	292352	6136239	1.02	0.86	-0.02	1.04
E114	292168	6136132	1.19	0.69	-0.09	0.92
E115	292890	6135400	1.01	0.64	-0.02	0.74
E116	292989	6135579	1.55	0.72	0.02	1.24
E117	293349	6135403	2.01	0.67	-0.04	0.74
E118	293254	6135147	1.05	1.03	-0.13	1.12
E119	293343	6134956	1.98	0.97	0.11	1.10
E120	293848	6135338	1.97	0.63	0.05	0.74
E121	293961	6135197	2.49	1.45	0.36	1.95
E122	294840	6135463	1.08	0.87	-0.11	1.06
E123	294849	6135259	1.36	0.62	-0.11	1.27
B0	301153	6123099	2.20	0.83	-0.13	1.02
B1	300233	6123337	2.42	0.64	-0.04	1.00
B2	299479	6123908	1.97	0.68	-0.05	0.98

Sample	X	Y	Mean Size	Sorting	Skewness	Kurtosis
B3	298820	6124639	2.14	0.67	-0.02	0.96
B4	298312	6125424	1.57	0.69	-0.05	0.98
B5	297756	6126266	1.57	0.57	-0.01	0.96
B6	297407	6127163	1.24	0.59	-0.01	0.97
B7	297208	6128139	1.20	0.69	-0.03	0.97
B8	297010	6128980	1.11	0.54	-0.02	0.97
B9	296889	6130121	1.09	0.50	-0.02	0.99
B10	296971	6131192	1.00	0.49	-0.01	0.99
B11	297279	6132150	1.40	0.50	0.03	0.99
B12	296741	6132273	1.83	0.57	0.01	0.95
B13	296072	6133072	1.57	0.50	-0.01	0.98
B14	295860	6134124	1.55	0.49	-0.02	0.99
B15	295955	6135061	1.34	0.50	0.01	0.98
B16	300239	6149958	2.22	0.46	0.00	0.98
B17	295269	6135767	2.34	0.56	0.01	0.97
B18	294646	6136534	2.40	0.50	0.03	0.99
B19	294275	6137457	2.08	0.55	-0.01	0.97
B20	294160	6138449	1.79	0.56	0.00	0.95
B21	294193	6139452	1.94	0.53	0.00	0.97
B22	294237	6140454	1.82	0.55	0.02	0.94
B23	294353	6141450	1.21	0.62	0.02	0.96
B24	294528	6142437	1.49	0.60	0.01	0.93
B25	294766	6143407	1.45	0.60	0.02	0.93
B26	295077	6144357	1.31	0.63	0.01	0.95
B27	295465	6145282	1.30	0.61	0.02	0.95
B28	295923	6146161	1.41	0.56	0.01	0.96
B29	296449	6147010	1.77	0.55	0.01	0.94
B30	297030	6147818	1.80	0.56	0.01	0.94
B31	297685	6148575	1.90	0.50	0.02	0.98
B32	298432	6149233	2.13	0.46	-0.02	0.98
B33	299277	6149773	2.18	0.51	-0.02	0.97
O1	299763	6149480	2.32	0.55	0.03	0.97
O2	299779	6148479	2.50	0.62	0.00	0.93
O3	299799	6147474	1.20	1.21	0.07	1.12
O4	298817	6148461	2.61	0.55	0.00	0.94
O5	298837	6147456	2.54	0.66	-0.02	0.97
O6	297823	6147437	2.39	1.11	-0.32	2.32
O7	297839	6146436	1.70	0.86	0.16	1.00
O8	296825	6146418	2.50	0.53	0.04	0.96
O9	296834	6145419	2.64	0.64	0.01	0.95
O10	296850	6144418	2.67	0.70	-0.02	0.94
O11	295841	6144394	2.36	0.71	-0.08	1.04
O12	295861	6143389	2.52	0.60	0.01	0.93
O13	295878	6142389	2.22	0.66	-0.04	1.00
O14	295120	6142487	2.32	0.75	-0.15	1.24

Sample	X	Y	Mean Size	Sorting	Skewness	Kurtosis
O15	294877	6141358	2.27	0.70	-0.03	0.96
O16	295889	6141382	2.43	0.63	0.00	0.96
O17	295905	6140381	2.17	0.70	0.03	0.95
O18	294893	6140357	2.24	0.76	-0.10	1.12
O19	294913	6139352	1.94	0.65	-0.07	1.06
O20	295925	6139376	2.29	0.72	0.00	0.92
O21	295941	6138376	2.76	0.63	-0.03	0.96
O22	294929	6138351	2.88	0.60	-0.04	0.96
O23	294938	6137353	2.69	0.75	-0.09	1.05
O24	295950	6137377	2.61	0.65	0.03	0.97
O25	295966	6136376	1.69	0.54	-0.02	0.93
O26	297132	6135047	2.87	0.88	0.00	0.96
O27	296175	6134876	1.87	0.69	-0.02	0.95
O28	296394	6133874	2.55	1.01	-0.11	1.12
O29	297352	6134044	2.76	0.97	0.09	0.97
O30	296685	6132881	1.64	0.62	0.02	0.94
O31	297435	6131698	1.56	0.63	0.03	0.95
O32	298067	6131003	0.58	0.83	-0.15	1.01
O33	297344	6130613	1.82	0.81	0.02	0.94
O34	298254	6130108	0.69	0.74	-0.03	0.92
O35	297271	6129567	2.05	0.67	0.00	0.97
O36	298335	6129164	3.24	1.05	-0.08	0.95
O37	298491	6128292	3.14	1.14	0.06	0.88
O38	297732	6127709	2.15	0.70	-0.03	0.96
O39	298800	6127314	1.77	0.77	0.11	1.08
O40	298072	6126708	2.18	0.70	-0.01	0.96
O41	299274	6126490	1.78	0.74	0.08	1.04
O42	298576	6125863	2.07	0.80	-0.09	1.05
O43	299071	6125021	2.30	0.68	-0.06	1.02
O44	299681	6124375	2.48	0.61	0.00	0.95
O45	300364	6125043	-0.63	0.93	0.83	0.37
O46	301085	6124597	1.60	0.78	0.02	1.00
O47	300436	6123915	2.67	0.61	-0.01	0.96
O48	301310	6123507	0.68	1.58	0.03	0.90
O49	301783	6124154	1.67	0.69	0.00	0.96
O50	301448	6151034	2.15	0.88	-0.11	0.93
O51	301607	6150928	2.23	0.91	-0.14	0.93
O52	301821	6150796	1.39	1.06	0.35	1.17

Appendix 4- (Carvalho and Woodroffe, 2015)

Carvalho, R. C. & Woodroffe, C. D. (2015). Rainfall variability in the Shoalhaven River catchment and its relation to climatic indices. Water Resources Management, 29 (14), 4963-4976.

Appendix 5 – SEM images of estuarine sediments

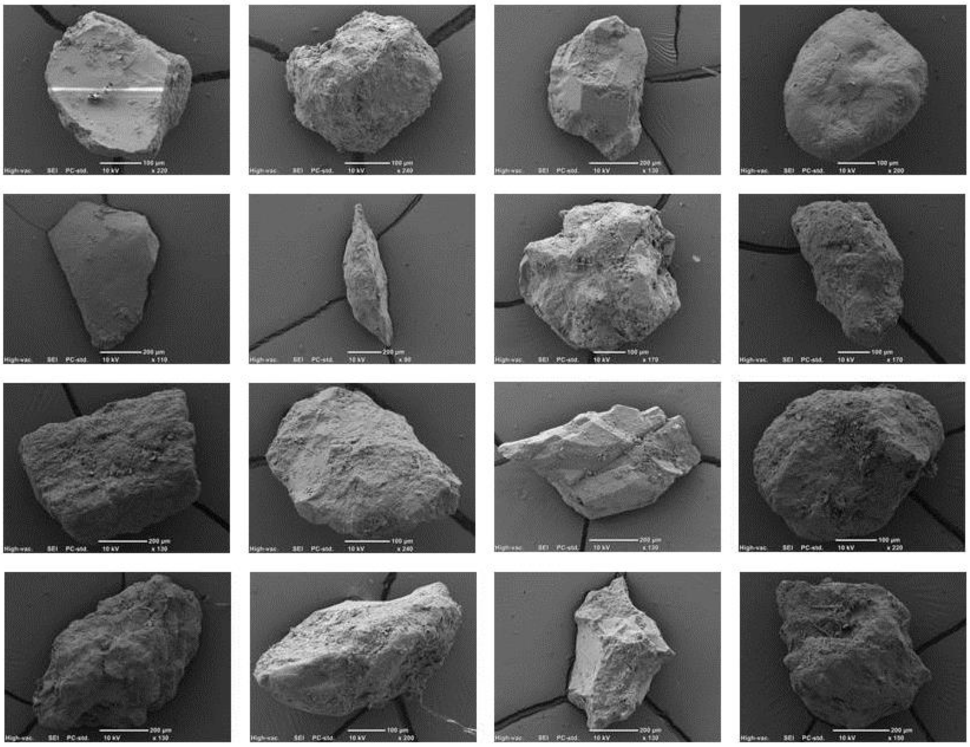

Figure A5.1 SEM images of quartz grains in the 1-2 phi fraction in sample E58, located upstream of Pig Island. Individual grains varied from very angular to rounded and most of them were chemically weathered.

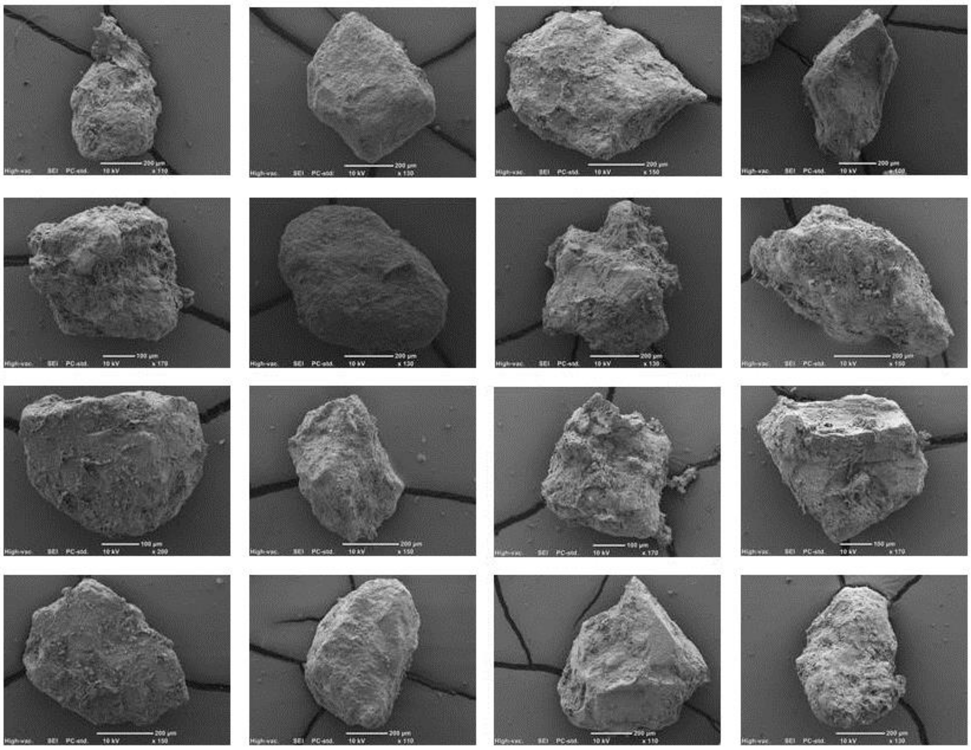

Figure A5.2 SEM images of quartz grains in the 1-2 phi fraction in sample E76, located upstream of Numbaa Island. Individual grains varied from angular to rounded and all of them were strongly chemically weathered.

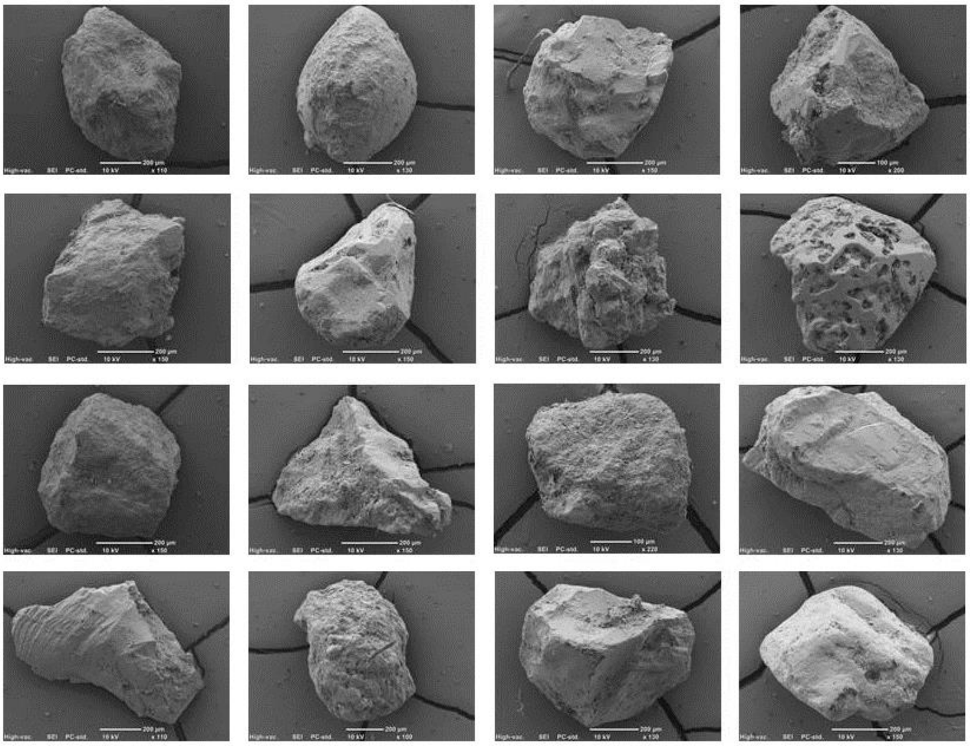

Figure A5.3 SEM images of quartz grains in the 1-2 phi fraction in sample E93, located in front of Old Man Island. Individual grains varied from angular to rounded and all of them were chemically weathered.

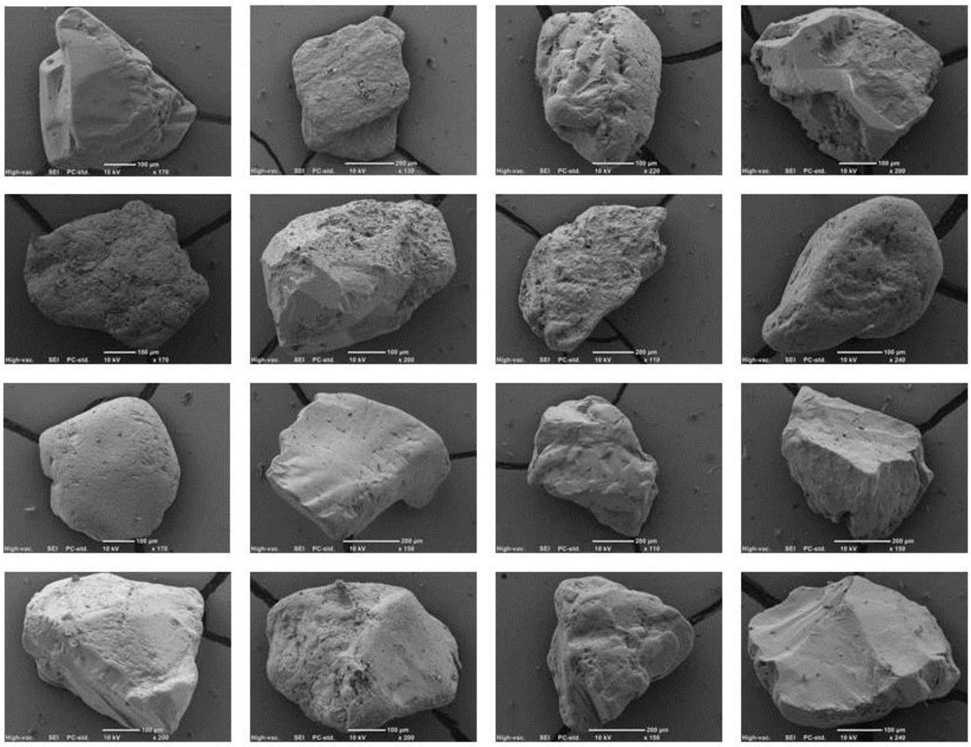

Figure A5.4 SEM images of quartz grains in the 1-2 phi fraction in sample E106, located at Shoalhaven Heads. Individual grains were mostly sub-angular with varying degrees of chemical weathering.

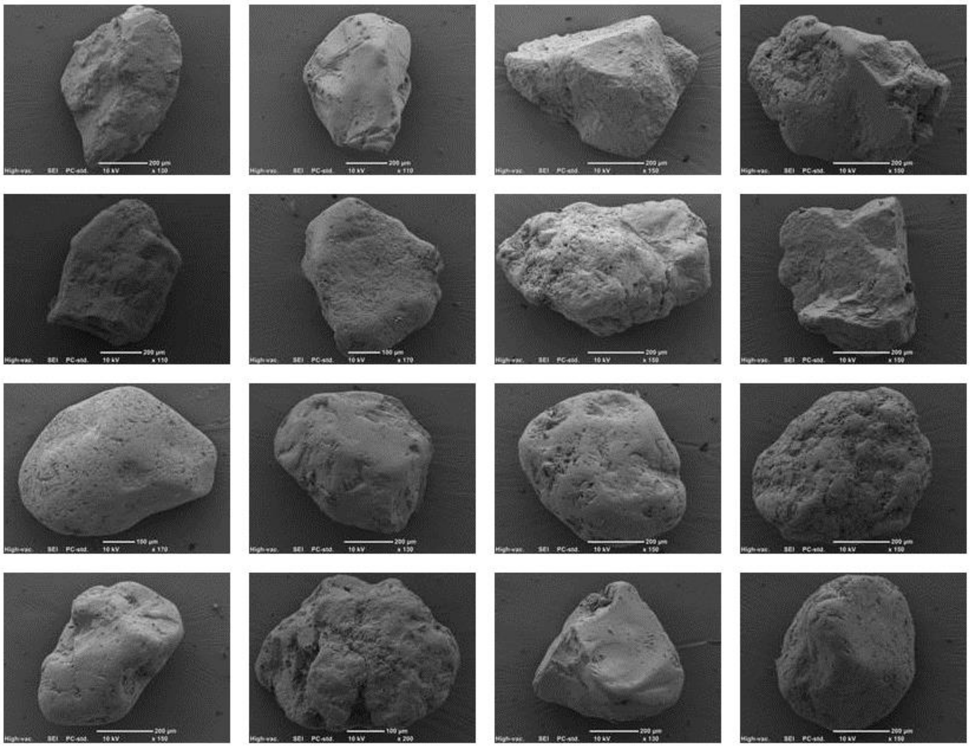

Figure A5.5 SEM images of quartz grains in the 1-2 phi fraction in sample E113, located at the Crookhaven channel. Individual grains were sub-angular to rounded and chemical weathering was weak or absent.

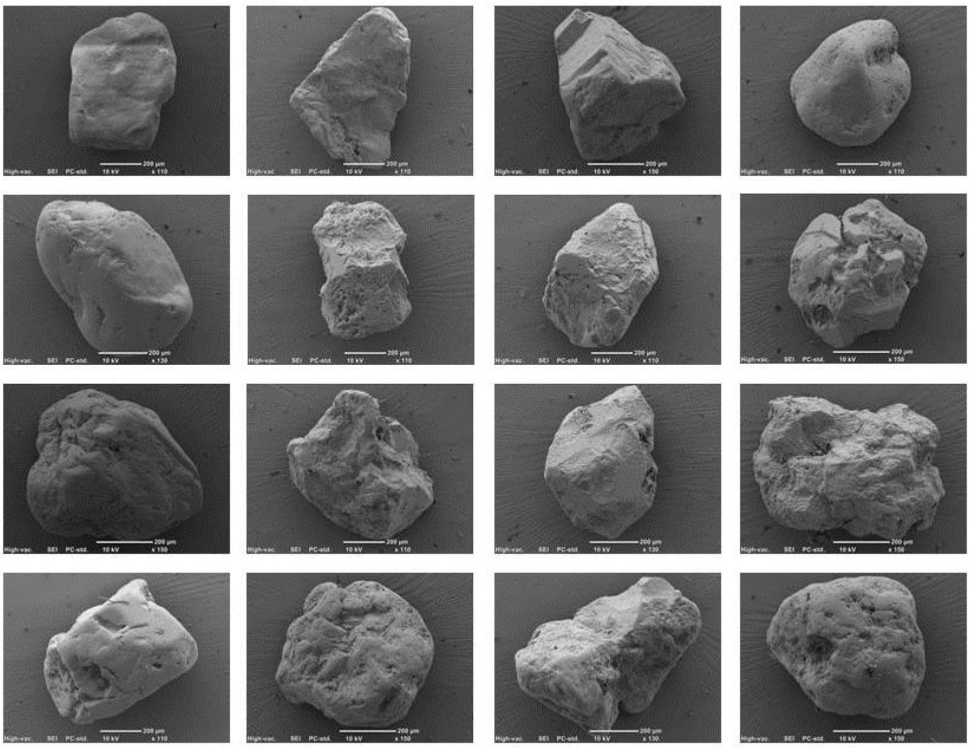

Figure A5.6 SEM images of quartz grains in the 1-2 phi fraction in sample E122, located at Crookhaven Heads. Individual grains were sub-angular to sub-rounded and chemical weathering was weak or absent.

Appendix 6 – SEM images of beach sediments

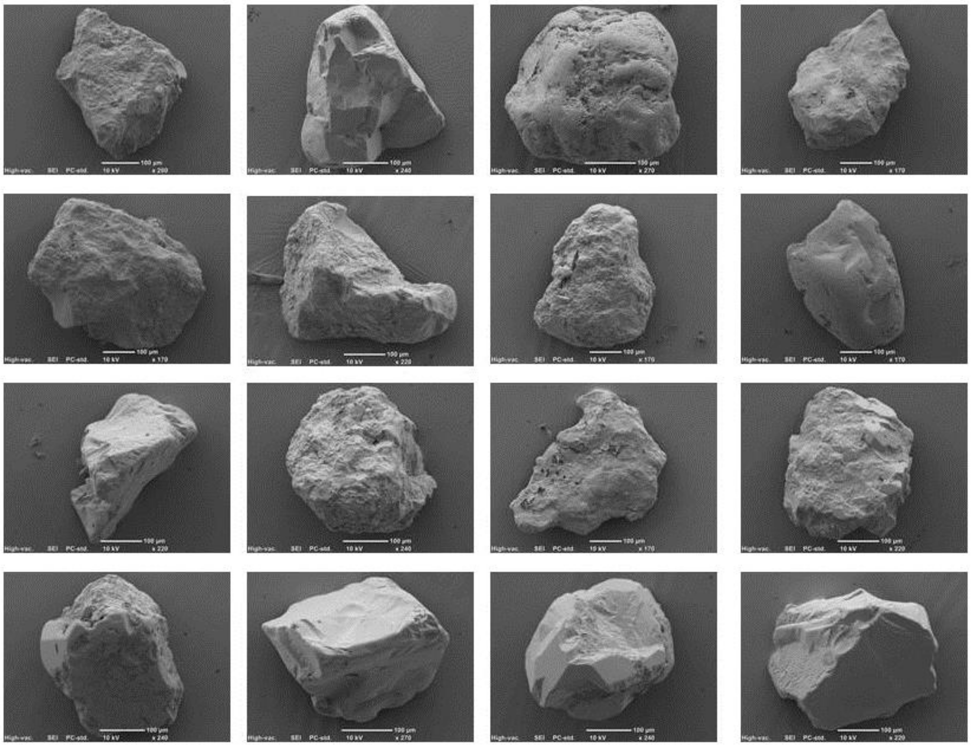

Figure A6.1 SEM images of quartz grains in the 1-2 phi fraction in sample B33, located at Gerroa. Individual grains varied from angular to sub-rounded. Most grains were chemically weathered, whereas some had fresh surfaces.

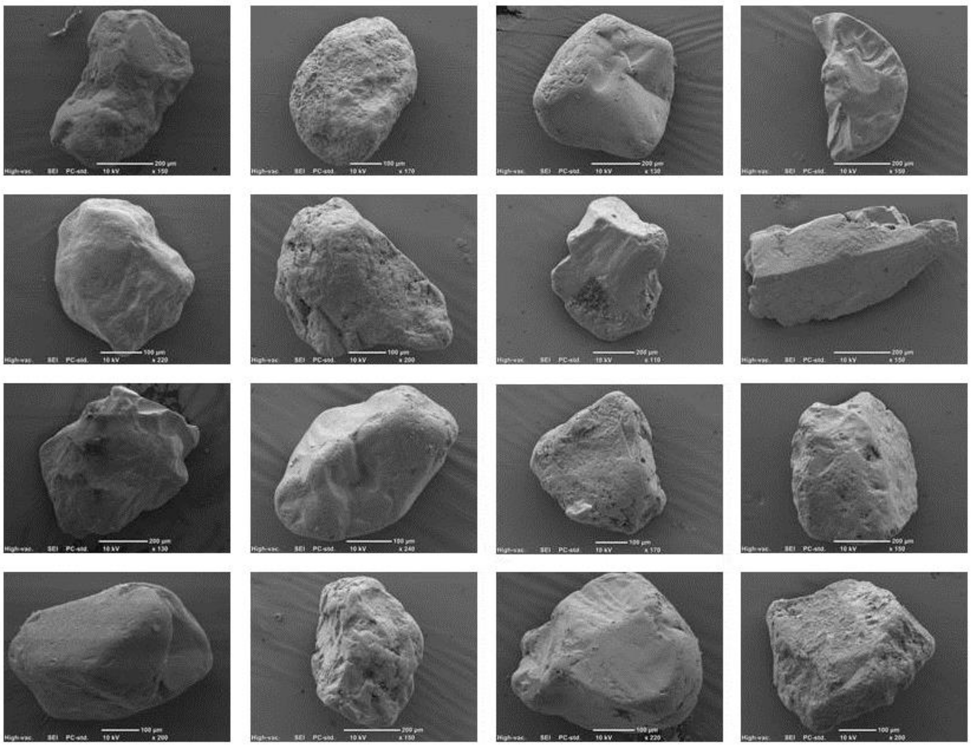

Figure A6.2 SEM images of quartz grains in the 1-2 phi fraction in sample B27, located 5 km north of Shoalhaven Heads. Individual grains were mostly high spherical and rounded to angular. Most grains were chemically weathered, whereas some had fresh surfaces.

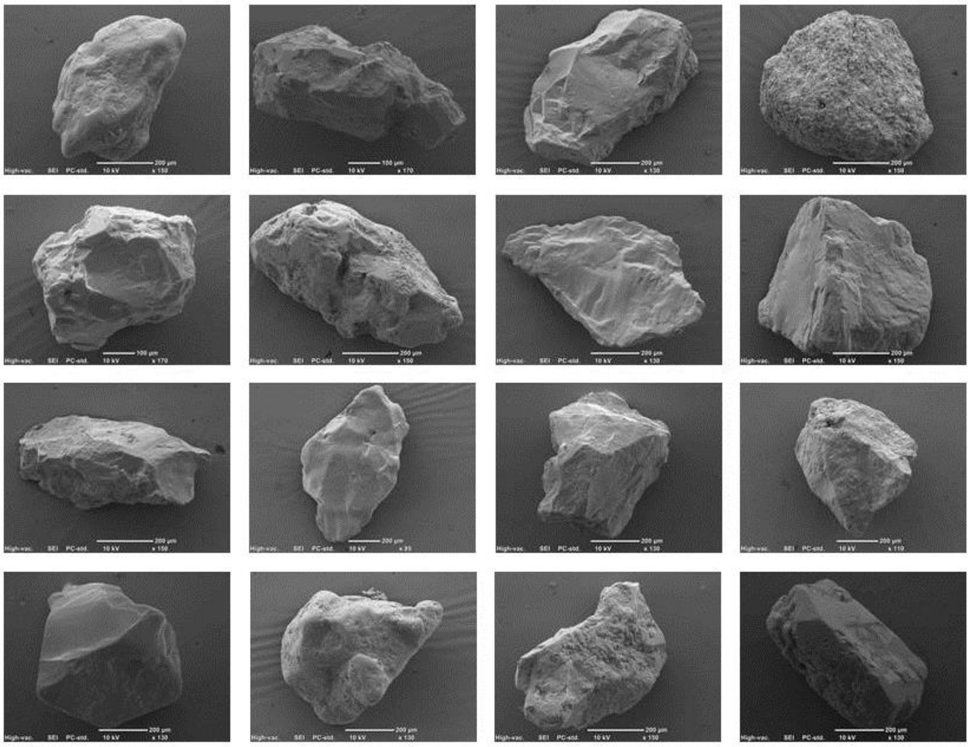

Figure A6.3 SEM images of quartz grains in the 1-2 phi fraction in sample B22, located at Shoalhaven Heads. Individual grains had low sphericity and were very to sub-angular. Some of the grains presented signs of strong chemical weathering, whereas others had fresh surfaces.

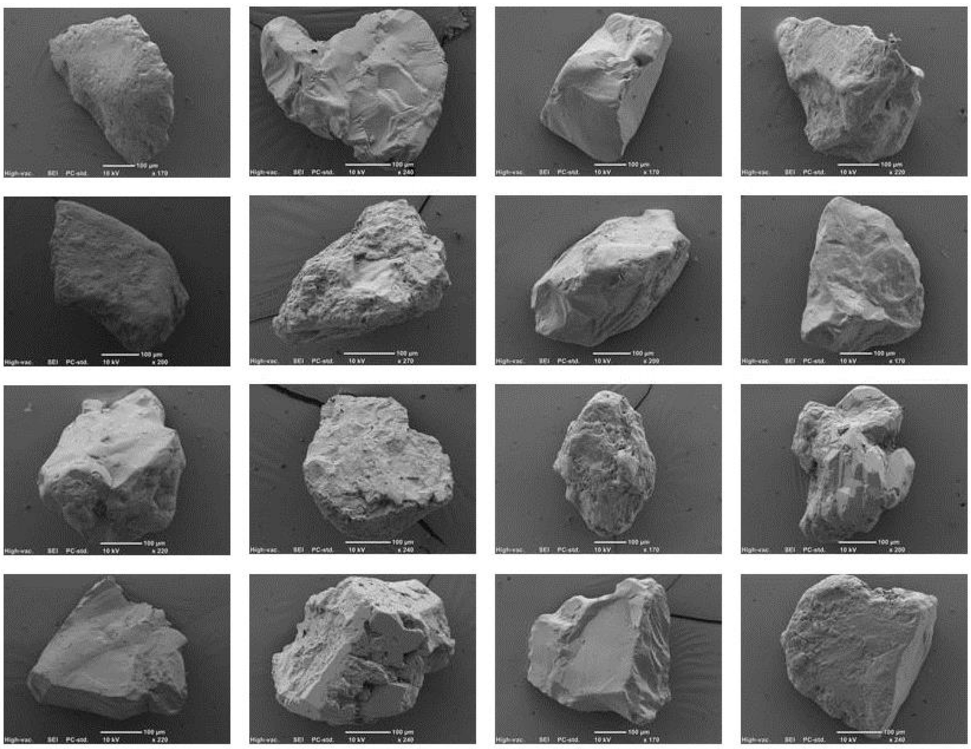

Figure A6.4 SEM images of quartz grains in the 1-2 phi fraction in sample B18, located at Comerong Island. Individual grains were very to sub-angular. Some of the grains presented signs of strong chemical weathering, whereas others had fresh surfaces.

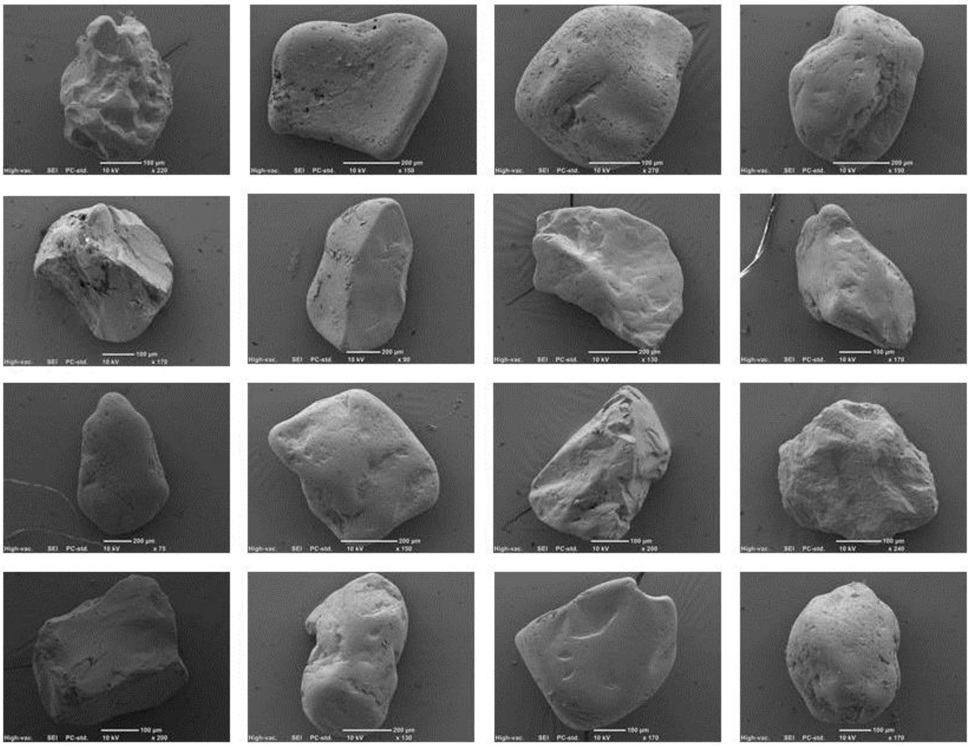

Figure A6.5 SEM images of quartz grains in the 1-2 phi fraction in sample B14, located at Culburra. Individual grains varied from rounded to sub-angular and presented polished surfaces.

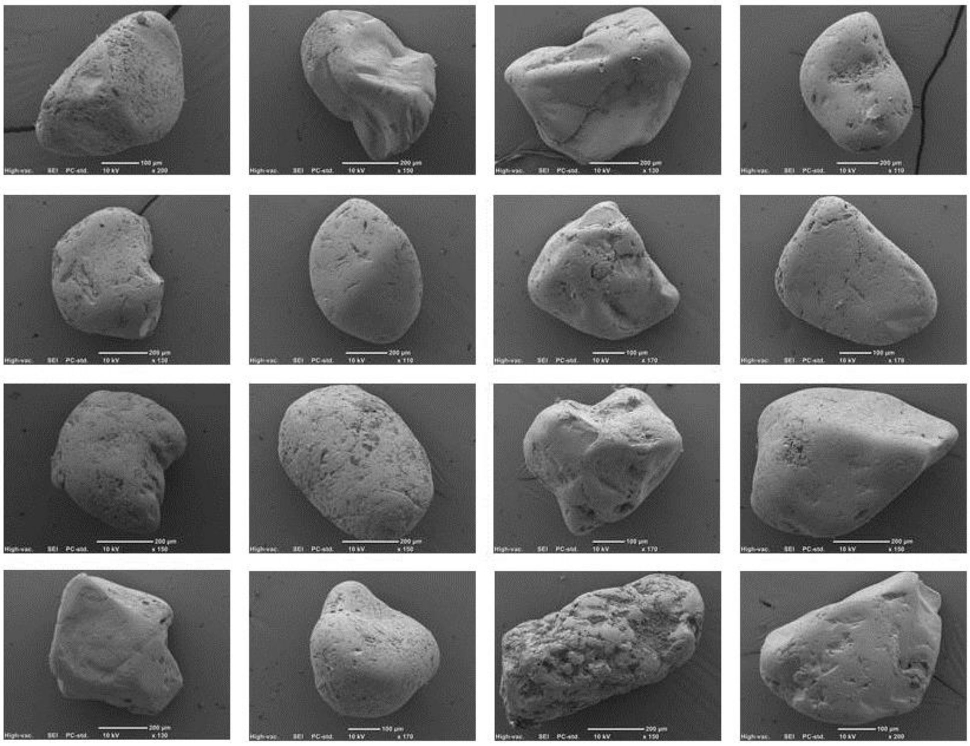

Figure A6.6 SEM images of quartz grains in the 1-2 phi fraction in sample B11 at Warrain. Individual grains were well rounded to sub-rounded and had mostly low to medium sphericity. Polished surfaces were present in most of the grains.

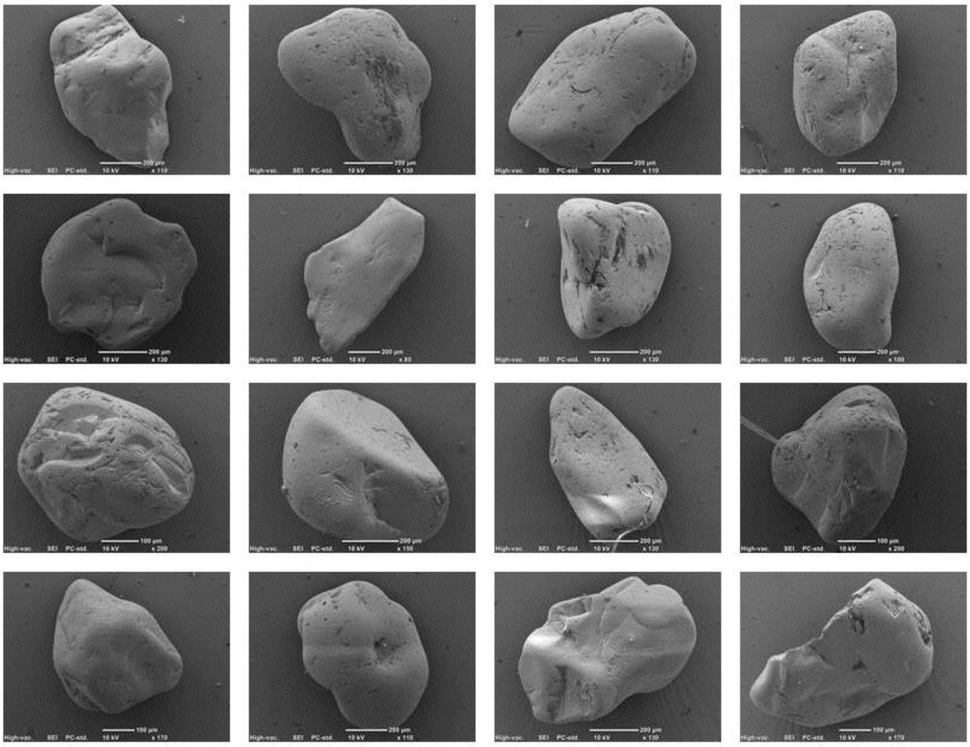

Figure A6.7 SEM images of quartz grains in the 1-2 phi fraction in sample B7, located between Kinghorn Point and Hammerhead Point. Individual grains varied from sub-rounded to rounded and had mostly low to medium sphericity. Polished surfaces were present in most of the grains.

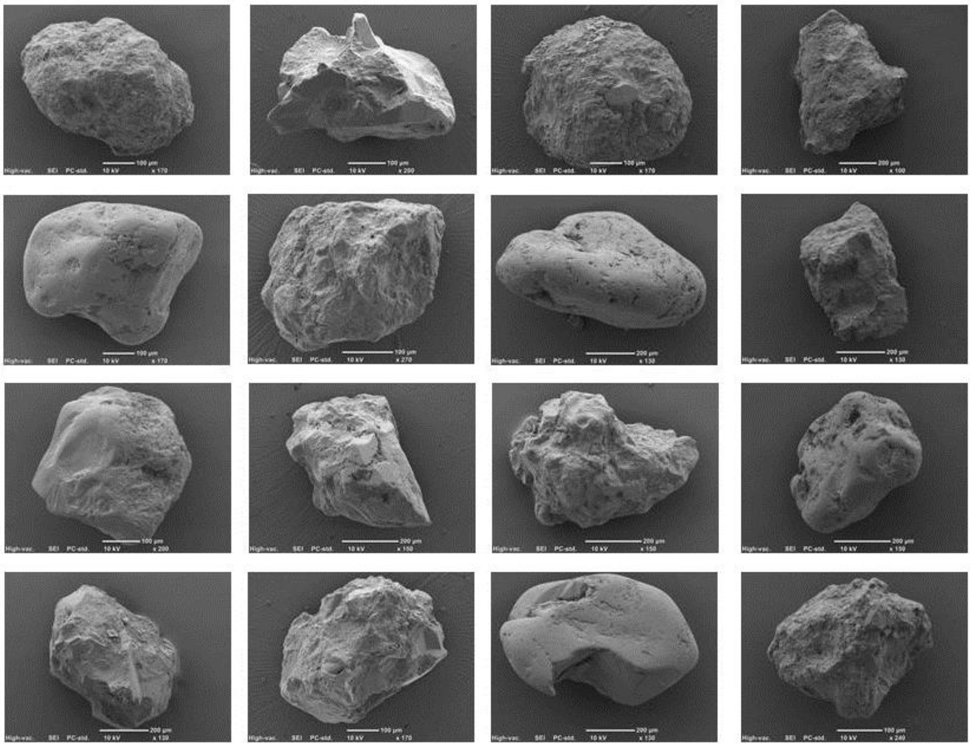

Figure A6.8 SEM images of quartz grains in the 1-2 phi fraction in sample B2, located at Currarong. Sphericity varied from low to high and roundness was angular to rounded. Some of the grains had polished edges, whereas most of them were chemically weathered.

Appendix 7- Beach behaviour between 2011 and 2012

This appendix details the monthly beach monitoring undertaken at profiles SH1-SH4 (Figure 2.7) that resulted in the beach envelope presented in Figure 5.16 and the subaerial section of the beach adjacent to the Surf Life Saving Club (SLSC) at Shoalhaven Heads, monitored using RTK-GPS mounted to an all-terrain vehicle (ATV) (Harley et al., 2011).

The beach state at the beginning of the monitoring period (February/2011) contained cross-sections that varied from a low-gradient (0.04 -SH1) to relatively high-gradient beachfaces (0.1 -SH3). A 1 m berm could be observed on SH2, whereas surveys only started on SH4 in May/2011. Examination of changes in beach profiles and volumes between February/2011 and December/2012 revealed detailed short-term quantitative information depicted in Figure A7.1.

No significant change was noticed on SH1 until July/2012 when the beach eroded significantly, including the 0.5 m berm that had gradually formed over the previous months. By the end of the monitoring period, this northern end of the beach has not yet recovered its initial volume.

SH2 showed a continuous monthly loss of sand on the beachface and a gentle increase in the berm’s height until June/2012, when storm cut reshaped the beachface, leaving a steep scarp behind. The following months witnessed more erosion. The scarp receded further back, as more sand was removed from the profile. By October/2012, a toe deposit was observed on the scarp. Some sand was deposited in the swash zone in November/2012, but the swash deposit migrated landwards in December/2012.

No noticeable change was observed on SH3 until June/2011, when part of the beachface eroded. Two months later, the beachface recovered to its previous state, a process that was repeated another three times until August/2012. A berm was observed to form in September/2012, but was eroded in the following months. In December/2012, a reform of the berm was observed one more time.

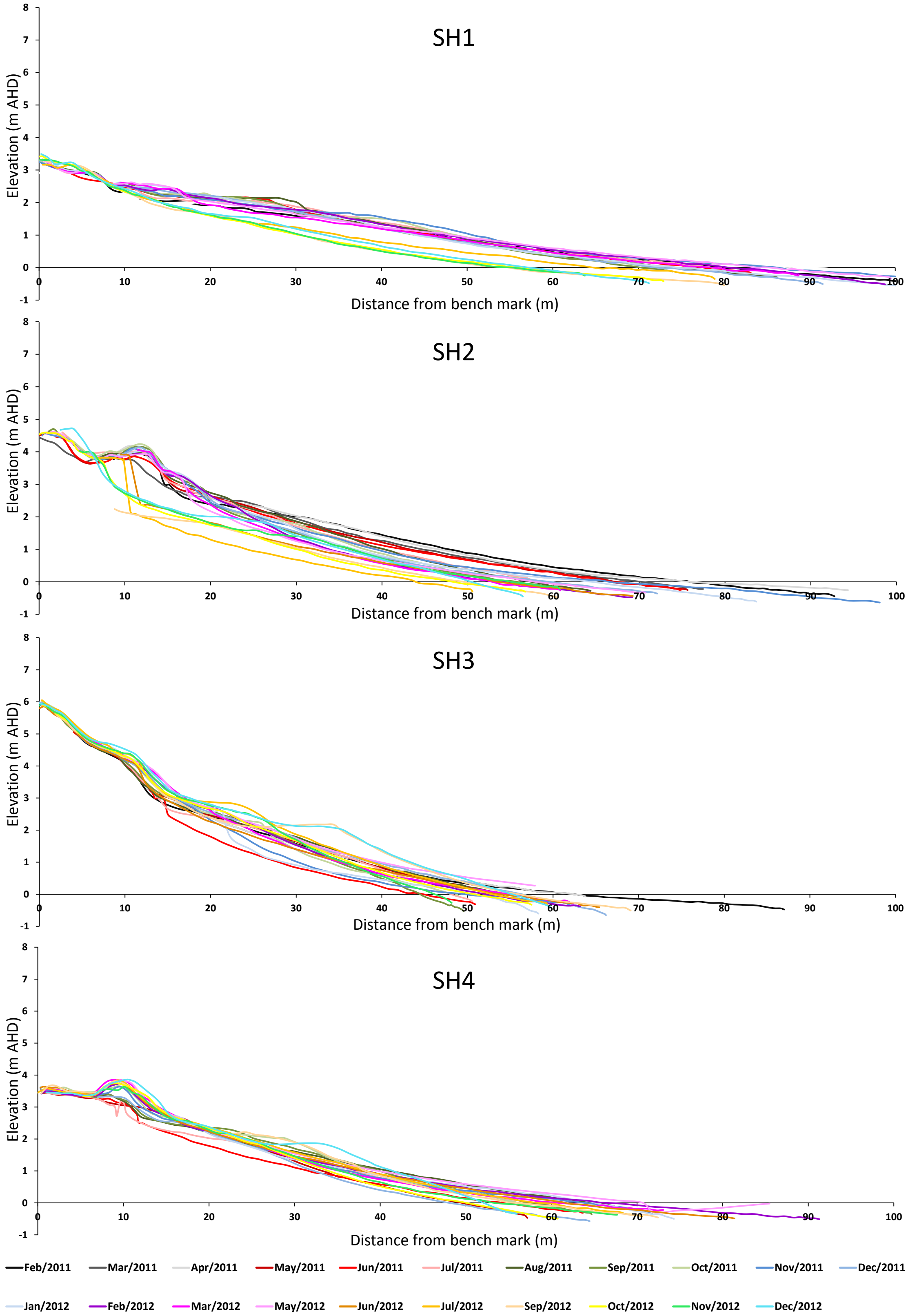

Figure A7.1 Monthly beach profile using RTK-GPS at Seven Mile Beach-Comerong Island between February/2011 and December/2012. Location of profiles is shown in Figure 2.7

SH4 experienced minor erosion in June/2011 and accretion in the following months, with the formation of a berm by October/2011. Then, it started receding again towards the end of 2011. By January/2012, the beach recovered its shape, remaining without significant change throughout the early months of 2012. A secondary berm started to form in September/2012, with subsequent erosion and reformation, in a similar pattern to the one on SH3.

In terms of volume (from the benchmark to 0 m AHD) (Figure A7.2), SH1 had 97.4 m^3/m when the monitoring started in February/2011. Five months later, an increase to 107.8 m^3/m was observed. Oscillation of ± 6 m^3/m happened throughout the end of 2011 and beginning of 2012. By March/2012, profile volume was reduced to 97.7 m^3/m, increasing to 107.3 in May/2012. Another volume reduction occurred in the months of July, September and by October/2012, beach volume at SH1 was the lowest (67 m^3/m) of the 2011-2012 monitored months. The volume increased a bit in the following months and finished with 72 m^3/m in December/2012.

The volume at SH2 was 104 m^3/m in March/2011. It oscillated a few m^3/m twice, before decreasing to 91 m^3/m in September/2012. Then, an increase was observed in the last two monitored months of 2011. Six months later, the volume dropped to 85 m^3/m and by July/2012 reached the lowest of 48.5 m^3/m. A recovery was observed in the final three months of 2012, when volume increased to 72 m^3/m.

At SH3, the volume that was 110 m^3/m in February/2011, decreased to 86 m^3/m in May/2011. A period of increase to 106.3 m^3/m in August/2011, was followed by a period of decrease to 91 m^3/m in November/2011. A major oscillation happened around the end of 2011 and beginning of 2012, when volume reached 118 m^3/m and then was reduced to 95 m^3/m. After that, an increasing trend started and volume reached 119 m^3/m in May/2012. The volume dropped another two times but never below 102 m^3/m, then an accretion period started in November and by December/2012 volume was 124 m^3/m, the highest registered in the 2011-2012 period.

The volume of SH4 at Comerong Island was 86 m^3/m in May/2011. It decreased to 78.8 m^3/m in June before increasing to 101 m^3/m in October. It decreased to 90 m^3/m in November/2011, but regained sand and reached 99.2 m^3/m in February/2012. A slight drop to 96 m^3/m occurred in March but three months later volume reached 100 m^3/m. After a minor oscillation in June and September, the beach volume increased to 105 m^3/m in December/2012.

A trend of erosion could be observed on SH1 and SH2, while deposition was observed on SH3 and SH4 between 2011 and 2012. SH2 showed the greatest spread of beach volume (σ= 18.4m^3/m), followed by SH1 (σ= 16.5 m^3/m), SH3 (σ= 9.3 m^3/m) and SH4 (σ= 7.5 m^3/m).

Volume calculations for the subaerial beach, monitored by RTK-GPS mounted on a ATV (Figure 2.7), was obtained by interpolating the irregularly spaced points according to the methodology described in section 2.14. The volume of 104 x 10^3 m^3 was observed in the area adjacent to the SLSC in February/2011 (Figure A7.). Throughout the monitoring period, six major volume losses occurred in the months of June, September and November/2011, March, June and October/2012. At the end of 2012, the subaerial beach volume was 109 x 10^3 m^3. The subaerial beach volume change adjacent to SLSC at Shoalhaven Heads varied from 73.3 to 115.5 x 10^3 m^3, (σ=10.2 x 10^3 m^3) and confirmed the trend of accretion for this part of the beach, as observed using profile SH3, that crosses the polygonal area surveyed with the ATV.

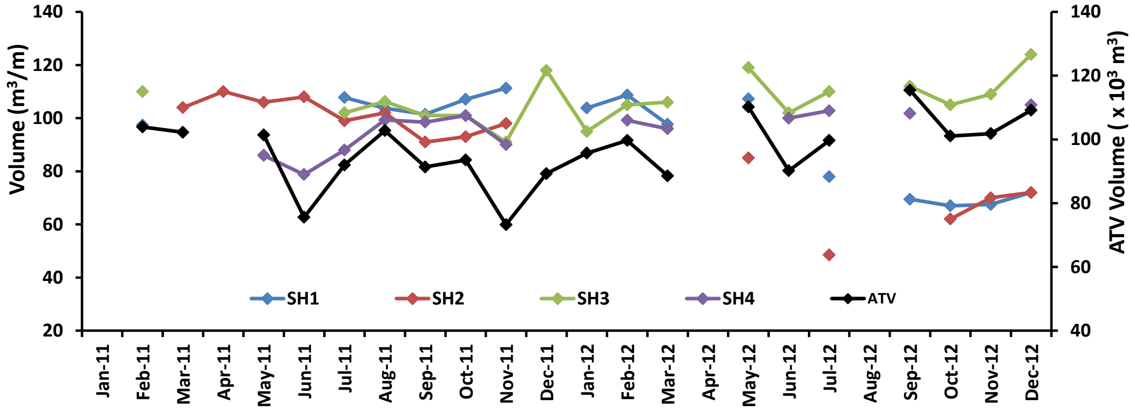

Figure A7.2 Monthly beach profile volume change above 0 m AHD at Seven Mile Beach-Comerong Island and monthly subaerial beach volume change above 0 m AHD adjacent to the SLSC at Shoalhaven Heads between 2011 and 2012

The deviations of Seven Mile Beach-Comerong Island beach width at each survey line from the mean for 2011-2012 are plotted in Figure A7.3. This plot indicates no consistent signs of beach rotation, determined by phase relation, between the northern (either SH1 or SH2) and the southern (SH4) profiles. When we try to relate accretion at SH1 and recession at SH4, or vice-versa, only the isolated month of October/2011 seemed to have behaved in a way that a negative phase relation could be established. Most monitored months show that they either accreted or receded at the same time. In between SH2 and SH4, the periods between May/2011 and August/2011, February/2012 and March/2012, and to a lesser extend May/2012 to June/2012 show some sort of negative phase relation. SH1 showed the greatest spread of beach width (σ= 10.2 m), followed by SH2 (σ= 8.6 m), SH4 (σ= 6.4 m) and SH3 (σ= 5.3 m).

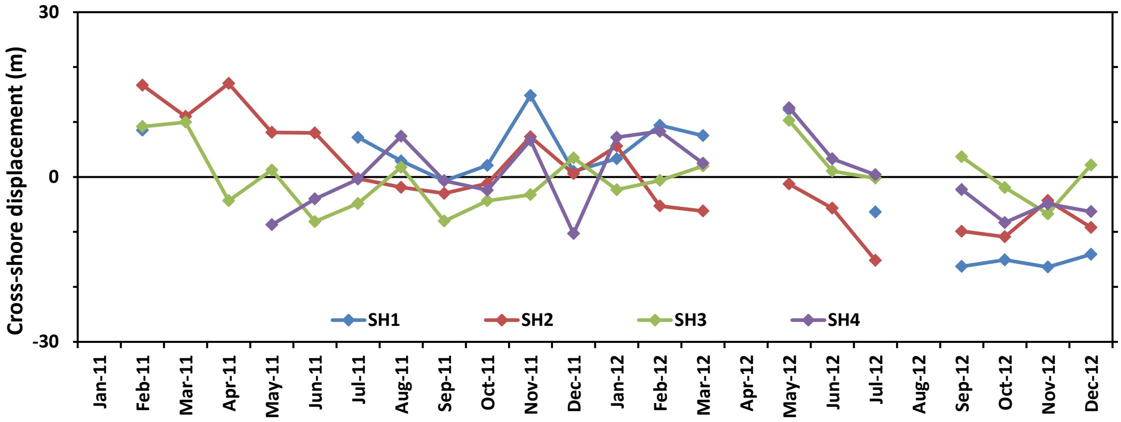

Figure A7.3 Seven Mile Beach-Comerong Island beach width deviation at each profile line from the mean position for 2011-2012

Another argument favoring the non existence of beach rotation at Seven Mile Beach-Comerong Island is the fact the the river mouth at Shoalhaven Heads remained closed during long time before the beginning of the monitoring period in 2011 and only opened up at the end of June/2013, not exerting influence in the phase relation carried out here, that could have been offset due to the possible input of sediments to the embayment.

Appendix 8- Beach behaviour between 2013 and 2015

This appendix details both the second part of the monitoring undertaken at profiles SH1-SH4, and the monthly beach monitoring of CUL1-CUL3 and WAR1-WAR3 (Figure 2.7), that resulted in the beach envelope presented in Figures 5.16 to 5.18. It took a year after December/2012 to restart the beach monitoring at Seven Mile Beach-Comerong Island, and expand to the embayments of Culburra and Warrain-Currarong. When the beach monitoring resumed in December/2013, the benchmarks for profiles SH1- SH4 were brought further landwards.

During this year gap, it seems that the deposition trend on top of profile SH1, that started in November/2012, continued and an incipient foredune had formed by the time the monitoring restarted in January/2014 (Figure A8.1). In February/2014, a berm started to develop. By April/2014, 0.6 m of sand accumulated at the the berm crest. During the following month the sand moved towards the foredune, and no berm was observed in July/2014. No major change was detected in August, but during September/2014, the profile became steeper indicating a loss of sand. The beach recovered from the loss during the last three months of 2014. Sand moved up in the profile by February-March/2015. In June/2015 the beachface became steeper once again and the beach lost sand. The beach face accreted in the following four months with little variation occuring. By November/2015 a new berm had started to develop.

It seems that the sand that was piling up on top of profile SH2 in December/2012 was removed from there by a recent storm during the year gap, as a new beach morphology was observed in January/2014, when monitoring resumed. A new 1.2 m steep scarp 0.5 m seawards from the 2011-2012 benchmark and a featureless gentle slope was observed. In February/2014, SH2 started to show signs of recovery as more sand was deposited in the lower beachface. Whereas not much change was detected in March, it gained sand in April and by May/2014 a berm had developed. In July/2014 sand migrated towards the scarp and the profile became flatter.

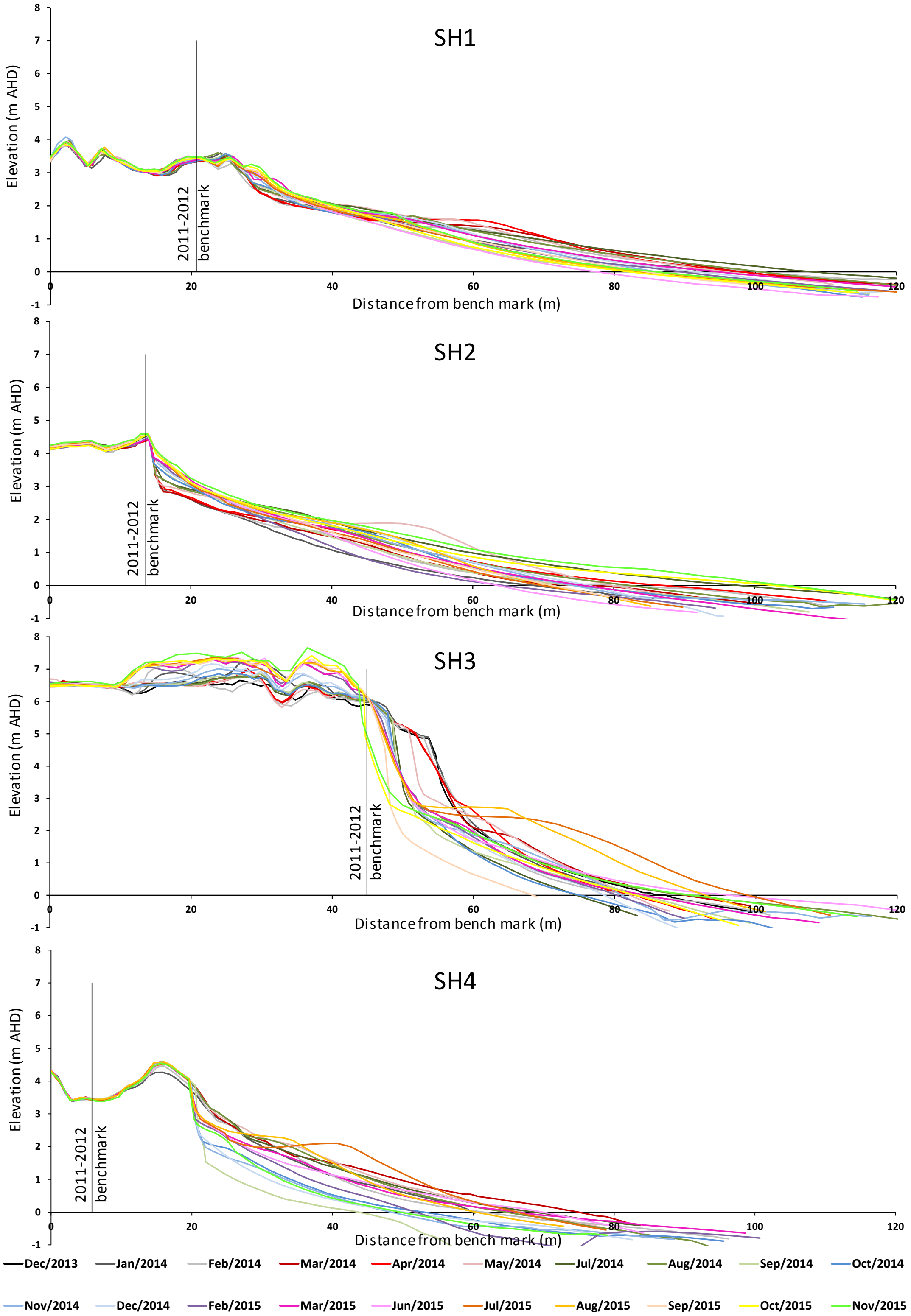

Figure A8.1 Monthly beach profile using RTK-GPS at Seven Mile Beach-Comerong Island between December/2013 and November/2015. Location of profiles is shown in Figure 2.7. Vertical bars indicate the location of benchmarks in 2011-2012 used for volume and beach width calculations throughout this thesis, despite the restablishment of new beachmarks further landwards for the 2013-2015 monitoring.

The following months of August and September/2014 the beachface experienced loss of sand, and restarted an accretional phase in October, that continued until December/2014, with of a new berm crest starting to develop. In February/2015, the SH2 profile was steep one more time and sand was lost. The beachface started to experience recovery in the month of March/2015, with alternating volume loss and gain in the months of June and July/2015, respectively. Volume increased further in August and went back to July's profile configuration in September/2015. In the last two months of monitoring, the beachface experienced considerable accretion.

In December/2013, SH3 had a 5 m scarp and the subaerial beach was restricted to less than 35 m wide. It is believed that a storm before the resumption of the monitoring at Seven Mile Beach-Comerong Island reshaped the beachface, as the beach morphology in front of the SLSC was quite different from the scarpless beach that existed in December/2012. The morphology did not change much in January/2014, but the beachface became steeper in February/2014 with the loss of sand in the lower parts of the profile. In April, the scarp retreated a bit followed by further recession in May/2014. By July, a vertical scarp was formed and loss of quite some volume happened. Alternating periods of gain and loss in the lower part of the profile happened in August and September/2014 respectively, with a further loss happening in October, ersulting in a return to morphology like that of July/2014. Then, accretion and partial loss was experienced in the lower part of the profile in November and December/2014. Not much change happened between February and June/2015. A large amount of sand accumulated up to 2.4 m AHD in July, migrating towards the scarp in August/2015. A vertical scarp was observed in September and subsequent retreat occurred in October and November/2015.

When the monitoring restarted at SH4 in January/2014, the profile configuration was not very different from December/2012. The inner berm crest was 0.4 m higher, the beachface was slightly concave and the secondary berm that started to form in December/2012, disappeared. Then, the berm crest increased in height in February/2014, with further increase, as well as, accretion in the lower profile, happening in March. A minor change occurred in May, when more sand migrated towards the upper part of the beachface. Sand loss occurred during July/2014, and not much happened in August. In September/2014, a vertical scarp was observed and substantial volume was lost. Some recovery occurred in the lower part of the profile in

October with little loss in the following months of 2014. By February/2015, the beachface recovered a bit and more recovery was observed in March/2015. The next surveyed month (June) registered a bit of fluctuation in the profile but no significant change in volume. However, in July/2015, a new berm had formed. Sand accumulated towards the scarp in August. Because of the flood event that opened Shoalhaven Heads in the days that followed the August monitoring, SH4 could not be surveyed in September and October. By November/2015, the erosion of most of the sand that accumulated in July and August occurred. Figures A8.2 and A8.3 show some of that morphological change experienced at SH1-SH4, when the monitoring resumed in December/2013 onwards.

Figure A8.2 Photos taken during different months of the monitoring period between December/2013 and November/2015 at SH1 (a and b) and SH2 (c and d). Rows a and c were taken towards the north, whereas rows b and d towards the south

Figure A8.3 Photos taken during different months of the monitoring period between December/2013 and November/2015 at SH3 (a and b) and SH4 (c and d). Rows a and c were taken towards the north, whereas rows b and d towards the south

In terms of volume (from the 2011-2012 benchmark to 0 AHD) (Figure A8.4), the beach at SH1 had 93.1 m^3/m in January/2014 and increased to a maximum of 112.9 m^3/m in July/2014 before starting eroding in August. During the September/2014 survey, a minimum volume of 83.3 m^3/m was estimated, with the beach recovering to approximately 100 m^3/m in the following months of 2014. A short oscillation occurred in the beginning of 2015 and by March the beach had a similar volume as in December/2014. In June/2015, the northern end of Seven Mile Beach-Comerong Island lost volume (83.9 m^3/m) one more time, and slowly recovered through the following months of 2015, reaching 96.4 m^3/m in November/2015.

The volume at SH2 followed a similar trend to SH1. SH2 had 58 m^3/m in January/2014, but rapidly increased to 105.8 m^3/m by July/2014, before losing sand in the following two months and reached 75.3 m^3/m in September. The end of 2014 was marked by recovery with volume increasing to 88.4 m^3/m. A substantial decrease to 64.5 m^3/m happened in February/2015 followed by quick recovery to 84.2 m^3/m in the following month. A second decrease was observed in June/2015 with volume estimated as 70.3 m^3/m. After that, the volume increased to reach a maximum of 114.4 m^3/m in November/2015, after a small oscillation that occurred in September/2015.

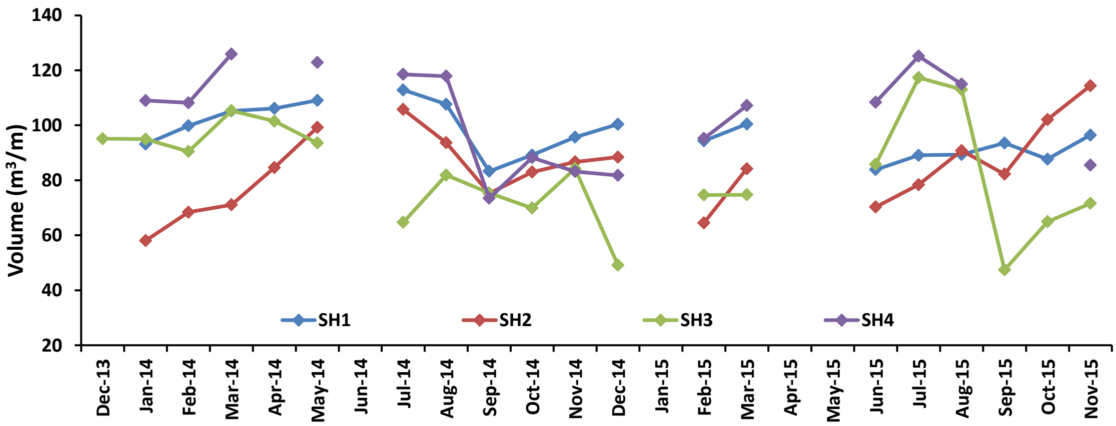

Figure A8.4 Monthly beach profile volume change above 0 m AHD at Seven Mile Beach-Comerong Island between 2013 and 2015

SH3 had 95.1 m^3/m in December/2013, decreasing to 90.5 m^3/m in February/2014 and recovering to 105.3 m^3/m in March. A loss of sand started in the following month and culminated in the drop to 64.7 m^3/m in July/2014. The beach at the SLSC oscillated twice in the second half of 2014 and was found with only 49.1 m^3/m in December/2014. Considerable recovery was observed in February/2015, and a major increase happened between June and July/2015 when the volume increased from 85.8 m^3/m to 117.3 m^3/m, respectively. In August/2015, SH3 lost 4.3 m^3/m. However, a major loss of sand occurred in September when volume dropped to 47.4 m^3/m, the lowest registered during the monitoring period. The following two months were marked by accretion and volume were calculated at 71.6 m^3/m in November/2015.

SH4 had 109 m^3/m of sand in January/2014. The volume increased to 125.9 m^3/m in March and slightly dropped to 122.9 m^3/m in May, 118.5 m^3/m in July and 117.8 m^3/m in August/2014. A major loss happened in the following month and volume reached as low as 73.5 m^3/m in September/2014. The beach at Comerong Island regained almost 15 m^3/m in October, but lost sand in the last two months of 2014, reaching 81.8 m^3/m in December/2014. An increase in volume was observed in the monitored months of February, March and June, and by July the volume reached 125.1 m^3/m. A reduction to 115 m^3/m was estimated for August and a further decrease in volume to 85.5 m^3/m was observed in November/2015.

A trend of erosion could be observed on SH1, SH3 and SH4, while deposition was observed on SH2 between 2013 and 2015. SH3 showed the greatest spread of beach volume (σ= 18.7m^3/m), followed by SH4 (σ= 16.6m^3/m), SH2 (σ= 14.3m^3/m) and SH1 (σ= 8.4m^3/m).

The deviations of Seven Mile Beach-Comerong Island beach width at each survey line from the mean for 2013-2015 are plotted in Figure A8.5. This plot indicates no consistent signs of beach rotation, determined by phase relation, between the northern (either SH1 or SH2) and the southern (SH4) profiles. When we try to relate accretion at SH1 and recession at SH4, or vice-versa, only the period between June and August/2015 behaved in a way that a negative phase relation could be established. The rest of the monitored months show that they either accreted or receded at the same time. In between SH2 and SH4, the periods between January and March/2014, June and August/2015 and the isolated months of March/2015 and November/2015 show some sort of negative phase relation. SH2 showed the greatest spread of beach width (σ= 11.7 m), followed by SH4 (σ= 9.2 m), SH1 (σ= 8.3 m) and SH3 (σ= 7.6 m).

In contrast to the first phase of the beach monitoring at Seven Mile Beach-Comerong Island, the lack of observed beach rotation during the 2013-2015 monitoring period, could have been influenced by the opening of the river mouth at Shoalhaven Heads which may have resulted in the possible input of sediments to the embayment in June/2013 and more recently in August/2015.

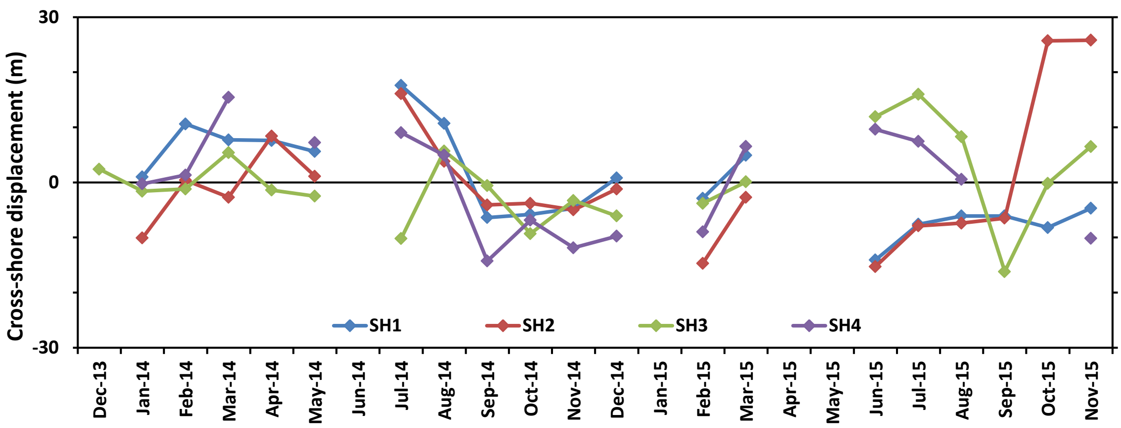

Figure A8.5 Seven Mile Beach-Comerong Island beach width deviation at each profile line from the mean position for 2013-2015

The beach monitoring at Culburra started in December/2013 (Figure A8.6). During the beginning of the monitoring, CUL1 had a 1.3 m steep scarp and a subaerial width of less than 40 m. During the first three months of 2014 the swash zone alternated between loss and gain of sand, followed by not much change during April/2014. By May/2014, a considerable amount of sand migrated to the upper part of the profile and the scarp was much smoother than in December/2013.

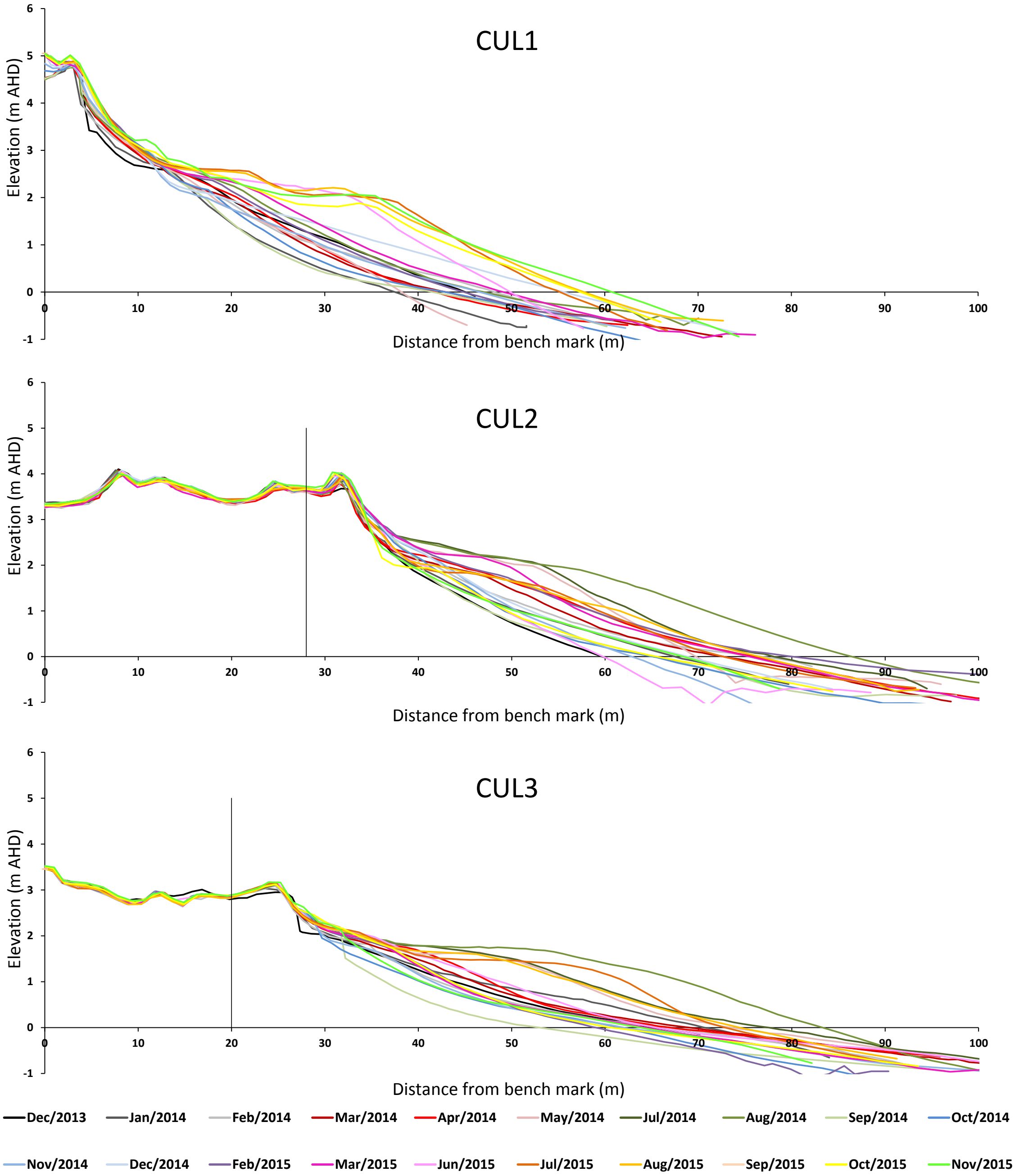

Figure A8.6 Monthly beach profile using RTK-GPS at Culburra between December/2013 and November/2015. Location of profiles is shown in Figure 2.7. Vertical bars at profiles CUL2 and CUL3 indicate benchmark for volume and beach width deviation calculations

Beach accretion was observed in the months of July and August/2014, whereas considerable loss of sand was observed in the lower beachface in September. Immediately south of the profile, a big scarp was formed extending for several hundred meters along the beach. The beginning of the recovery period that continued for another three months was observed in October/2014. In November/2014, the lower beachface continued to accrete and sand overtopped the foredune crest covering the benchmark. In December, more sand accumulated in the swash, foredune toe and more overtopping occurred, burying even further the benchmark.

In February/2015 the beach receded and the subaerial beach returned to the width as it was in December/2013. During the month of March the beach accreted a bit and three months later the beach accreted substantially and developed a berm. By July, the beach gained even more sand and a secondary berm was formed. From August/2015 until the end of the monitoring in November/2015, the beach profile at CUL1 remained very similar with slight changes in both swash and berm.

The beach profile at CUL2 was quite steep when the monitoring began in December/2013. The subaerial beach was less than 30 m in width representing the narrowest state during the two year monitoring period. Gradual accretion in the swash zone happened in the following five months and by May/2014 a berm was formed. Further accretion happened in July and by August/2014 a substantial volume of sand had been deposited on the beach since the beginning of the monitoring.

During September/2014, an erosive event brought back the profile configuration to a similar shape as in the first months of monitoring. Slow recovery occurred in the last three months of 2014. More accretion occurred in February/2015 and by March a new berm was formed. A new erosion event was observed in June/2015, with substantial recovering happening in the following month. The beach profile remained similar in August/2015, but experienced loss of sand in the October and signs of recovery by the end of the monitored period in November/2015. Another interesting aspect regarding the changes experienced by this part of the beach includes the accretion of the old beach berm crest during this two year window. An overall accretion of 0.4 m happened during this period.

At CUL3, in the southern end of Culburra Beach, the profile showed a 1 m scarp in December/2013. The scarp toe was filled in in January/2014 and the sand gained in the lower part of the profile was lost in February. Accretion commenced in March/2014. By May/2014 a secondary berm was formed, and further accretion was observed in July/2014. By August/2014 the beach profile experienced the biggest accretion phase of the monitoring period, with lots of sand deposited in the lower beachface representing the peak of volume during the two year monitoring.

An erosive event occurred in September/2014, leaving a new scarp located seawards from the original scarp that existed in December/2013. A gradual accretional phase started in October/2014 and continued until June/2015. By July, a lot of sand was deposited in the lower beachface and a secondary berm was forming. Another erosive event occurred in October/2015 resulting in beach volume loss and beach width reduction. Further volume loss was observed in November/2015. Figure A8.7 shows some of the morphological change experienced at CUL1-CUL3 between December/2013 and November/2015.

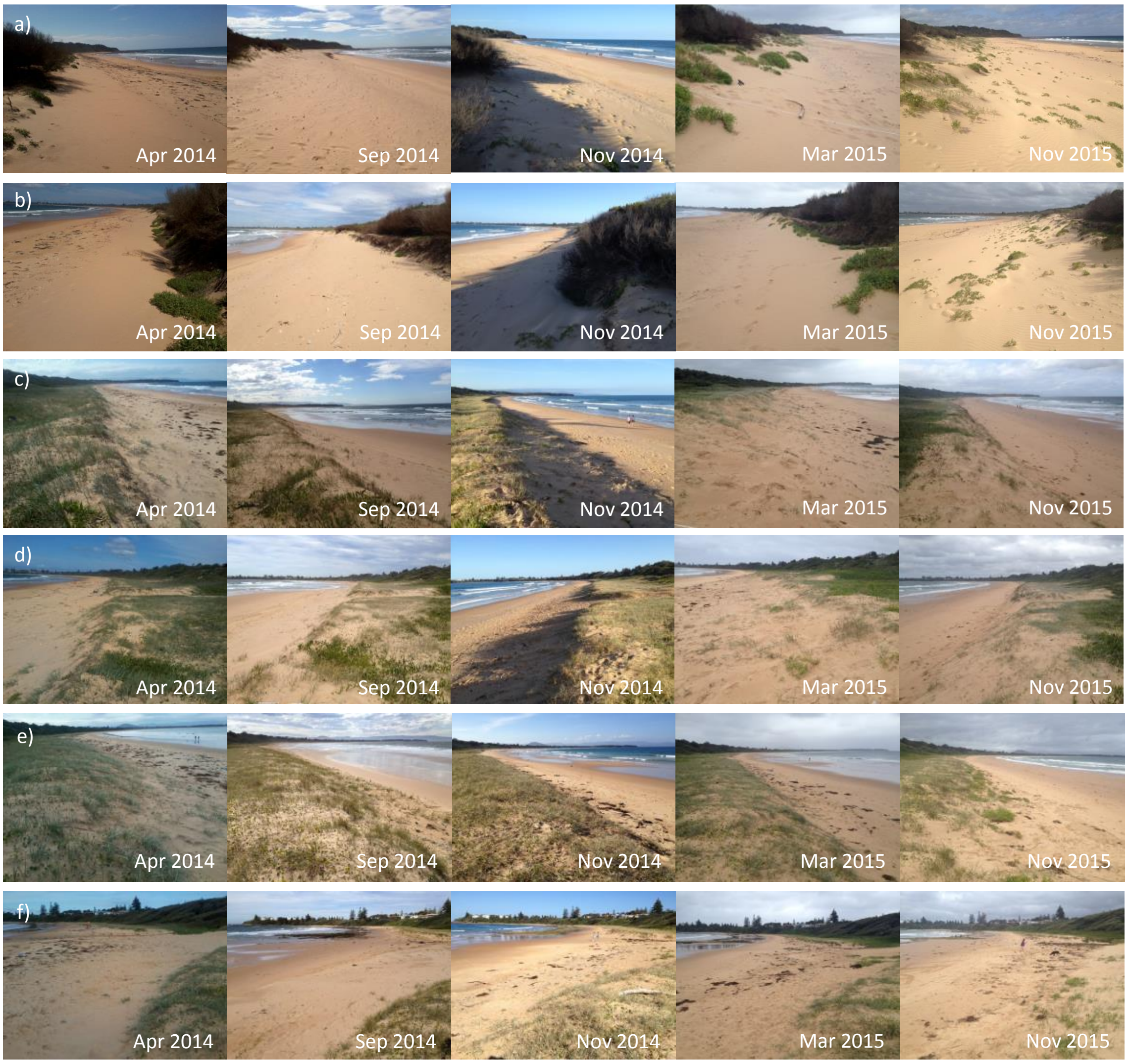

Figure A8.7 Photos taken during different months of the monitoring period between December/2013 and November/2015 at CUL1 (a and b), CUL2 (c and d) and CUL3 (e and f). Rows a, c and e were taken towards the north, whereas rows b, d and f towards the south

In terms of volume (Figure A8.8), the northern part of Culburra at CUL1 had a volume of 85.4 m^3/m of sand in December/2013. A decrease to 71.3 m^3/m occurred in January/2014 but regain happened in February. Volume oscillation followed in the next five months of 2014 and by August, the volume was 92 m^3/m. Another loss brought the volume back to 74.1 m^3/m in September/2014. After that, volume continued to increase until the end of the monitoring, reaching 124.9 m^3/m in November/2015. During this time, two small volume reductions of less than 8 m^3/m were observed in February/2015 and October/2015.

CUL2 had a volume of 52.2 m^3/m in December/2013 and a continued increase followed until August/2014, when it reached 104 m^3/m. A considerable reduction to 55.6 m^3/m happened in September and another accretion phase started the following month. By February/2015, the volume was 79.6 m^3/m. Whereas not much occurred in March/2015, another decrease was observed in June/2015 and volume was reduced to 58.7 m^3/m. An accretion pattern happened in the next two months with volume reaching 77.1 m^3/m in August/2015. The volume decreased to 57.2 m^3/m in October and regained some volume in November finishing the monitoring with 63 m^3/m.

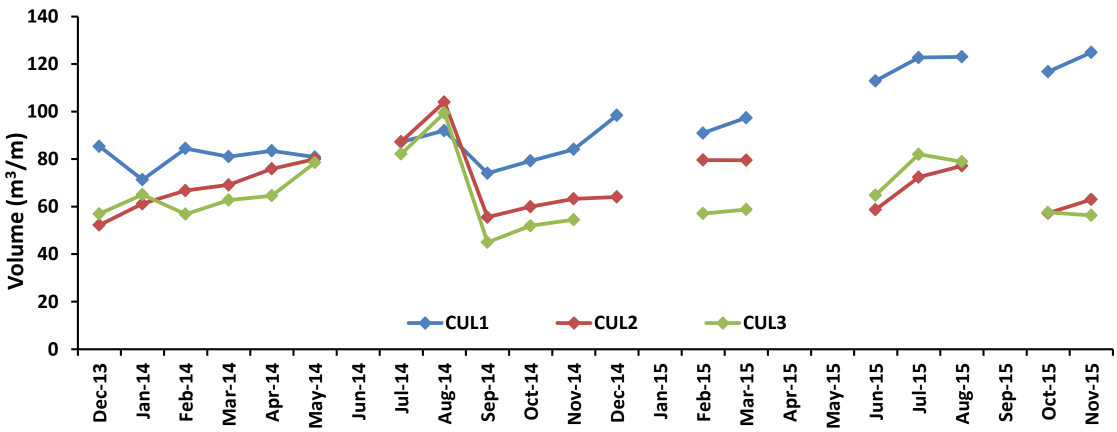

Figure A8.8 Monthly beach profile volume change above 0 m AHD at Culburra Beach between 2013 and 2015

CUL3 had 57 m^3/m of sand in December/2013; the volume increased to 65.1 m^3/m in January/2014. In February, the southern part of the beach lost the amount of sand that it had gained in January, but an accretion phase started in March/2014. By August/2014, the volume was 99.5 m^3/m, but was halved in September/2014. A slow recovery period started after that, but took 10 months to reach a volume of 82 m^3/m (July/2015). A decrease in volume was observed in the following months of 2015 until it reached 56.3 m^3/m in November/2015.

A trend of minor erosion could be observed at CUL2 and CUL3, while accretion was observed on CUL1 between 2013 and 2015. CUL1 showed the greatest spread of beach volume (σ= 16.9 m^3/m), followed by CUL3 (σ= 13.3 m^3/m), and CUL2 (σ= 12.5 m^3/m).

The deviations of Culburra beach width at each survey line from the mean are plotted in Figure A8.9. This plot indicates some evidence of beach rotation, determined by phase relation, between the northern (CUL1) and the southern (CUL3) profiles, during the first eight months of 2014, the last months of 2015, as well as, during isolated months of March/2015 and June/2015. Between December/2013 and July/2014, CUL1 and CUL3 had a quite strong negative phase relation. While CUL1 retreated, CUL3 accreted and vice-versa. However, between August/2014 and August/2015, no consistent negative phase relation could be observed. Moreover, it seems that a positive phase relation was established during several months, such as the periods between September and November/2014, and July and August/2015. CUL2 showed the greatest spread of beach width (σ= 7.2 m), followed by CUL3 (σ= 7.1 m) and CUL1 (σ= 6.9 m).

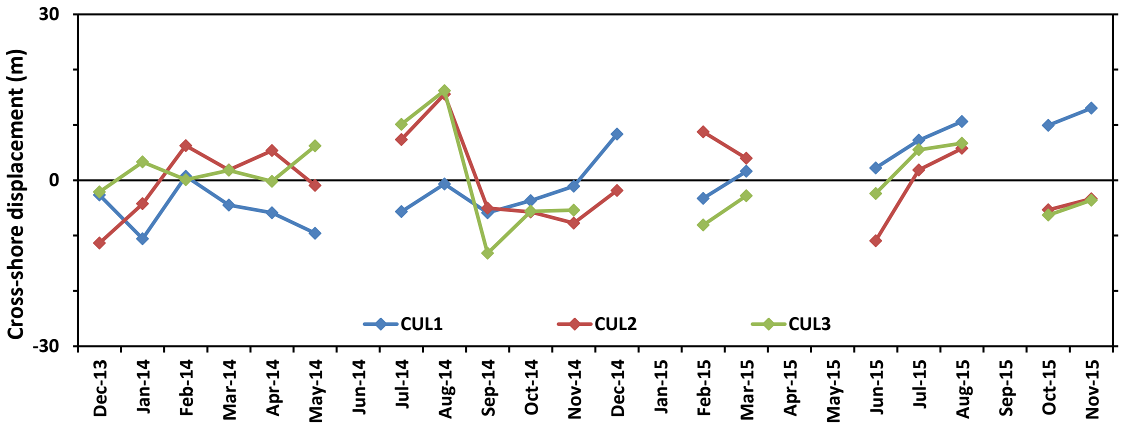

Figure A8.9 Culburra beach width deviation at each profile line from the mean position

The beach monitoring at Warrain-Currarong started in December 2013 (Figure A8.10). At the beginning of the monitoring, the beach slope at WAR1 was quite steep. Slow accretion happened in the early months of 2014 and by May/2014 a berm was formed. The disappearance of the berm was observed in July/2014 and not much change occurred in August. An erosive event happened in September/2014 bringing the profile to a similar shape as experienced in December/2013.

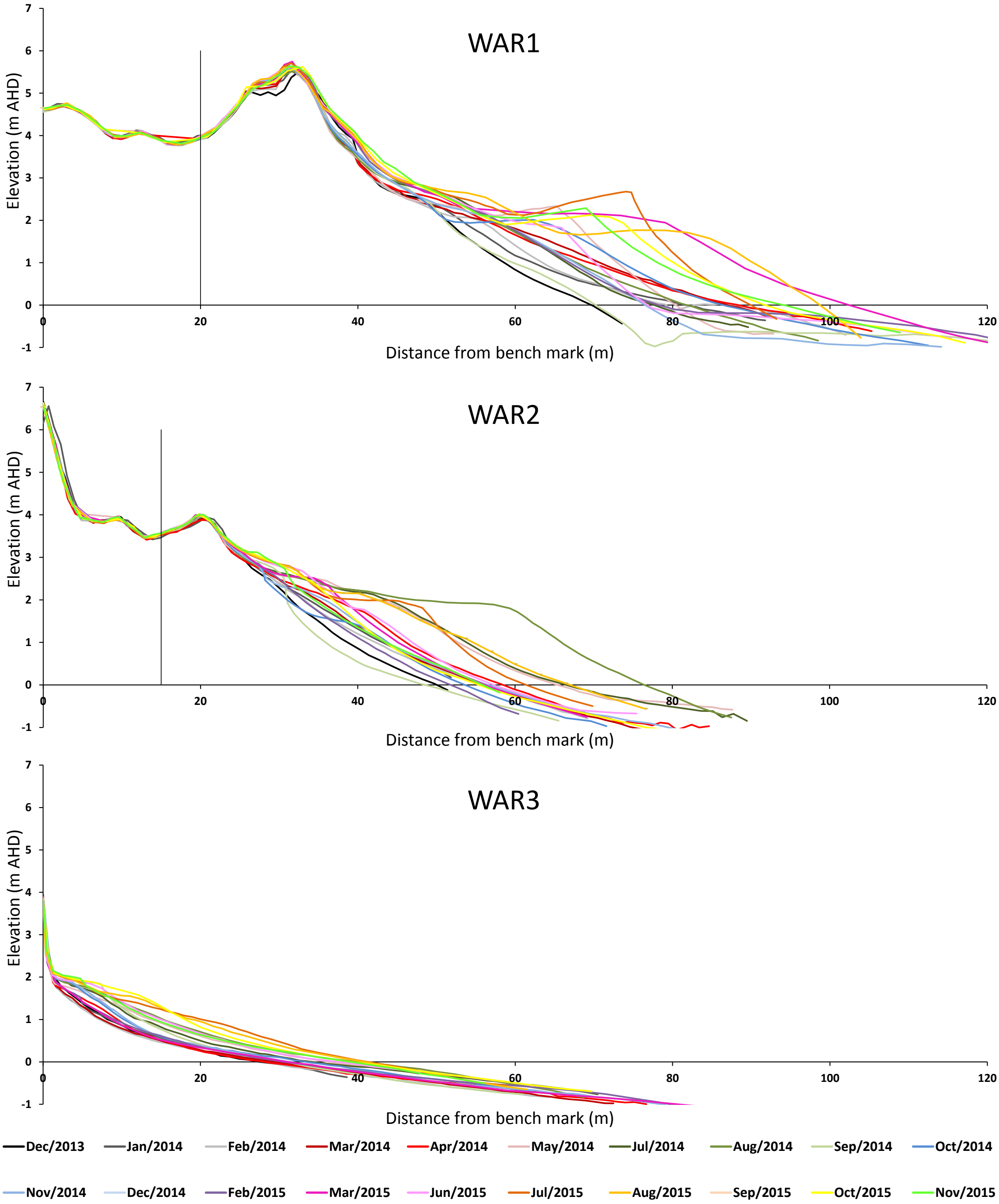

Figure A8.10 Monthly beach profile using RTK-GPS at Warrain between December/2013 and November/2015. Location of profiles is shown inFigure 2.7. Vertical bars at profiles WAR1 and WAR2 indicate benchmark for volume and beach width deviation calculations

Another berm started to form in October/2014 but this feature disappeared with the moviment up profile of the sand deposited in the berm in November/2014 and in the next monitored month of February/2015. A lot of sand was deposited in March/2015 and the subaerial beach had widened by more than 30 m since the beginning of the monitoring. By June/2015, the sand that had built up the beach disappeared from the beachface and only a two meter berm was left. Berm development recommenced in July/2015 and a higher berm crest (2.7 m) was created. In August, the berm formed in the previous month was smoothed out and by October, the sand that was observed in the lower part of the profile commenced to form a new berm once again, this time the profile configuration showed a much more landwards feature, that continued to migrate landwards until the end of the monitoring period in November/2015.

The distance between the benchmark and the mean water level (0 m AHD) at WAR2 was 50 m in December/2013, with the profile exhibiting continual slope seawards from the beach berm. The swash zone accreted at the beginning of 2014 and insignificant change occurred in February and March/2014. Sand built up a bit more in April and considerably more in May/2014.

Not much happened in the two months between May and July/2014. However, a big change was observed in August, with the middle of the beach at WAR2 gaining a lot of sand. An erosive event eroded the beach in September/2014. The beach began to recover in the following months of 2014, but oscillated, losing sand in February/2015, and regaining back in March. Between June and August/2015, a continuous accreting phase led to a profile configuration similar to July/2014. A quite significant loss of sand happened in the swash in October and a slightly more loss was observed in November/2015.

The southern end of Warrain-Currarong, at WAR3, had a continuous flat slope approximately 25 m long until the mean water (0 m AHD) at the beginning of the monitoring in December/2013. Small fluctuations occurred in the first months of 2014, leading to accretion in the upper part of the swash zone by the end of April/2014. In May, more deposition occurred all over the lower beachface, the beach accreted in width and volume. The upper part of the swash accreted slightly, while the lower part eroded in July/2014.

More accretion occurred in August/2014, whereas in September, a similar change in morphology to what was experienced in July occurred. The upper part of the swash accreted slightly forming a berm of approximately 2 m height, whereas the lower part eroded. An erosive event occurred in October/2014, whereas not much change happened in the following month. 2015 started with loss of sand in February. The beach profile configuration and volume became similar to what was observed at the beginning of the monitoring. The profile did not change significantly in following month. By June/2015, the beach accreted substantially, and continued to accumulate sand in the following month. After July/2015, the profile accreted in the upper part and eroded in the lower part of the swash zone. During the final month of the monitoring, the beach lost considerable volume of sand. Figure A8.11 shows some of that morphological change experienced at WAR1-WAR3 between December/2013 and November/2015.

Figure A8.11 Photos taken during different months of the monitoring period between December/2013 and November/2015 at WAR1 (a and b), WAR2 (c and d) and WAR3 (e and f). Rows a, c and e were taken towards the north, whereas rows b, d and f towards the south

In terms of volume (Figure A8.12), WAR1 increased from 140.1 m^3/m in December/2013 to 172.6 m^3/m in May/2014. A decrease in volume to 160.6 m^3/m was observed in July/2015 and to 143.9 m^3/m in September/2015 after a slight increase in August. WAR1 oscillated one more time in October and November/2015 finishing the month of monitoring with a volume of 160.4 m^3/m. After two month without surveys, the volume increased slightly to 162.8 m^3/m in February/2015. A major gain was observed in March/2015 with volume increasing to 211.1 m^3/m. Three months later, 169.4 m^3/m was estimated and a quick recovery to 203.3 m^3/m occurred in July/2015. After the slight increase of 1.3 m^3/m that happened in August, another loss of sand was observed and beach volume was reduced to 189 m^3/m in October/2015. At the end of the monitoring period the volume at WAR1 was 194.6 m^3/m.

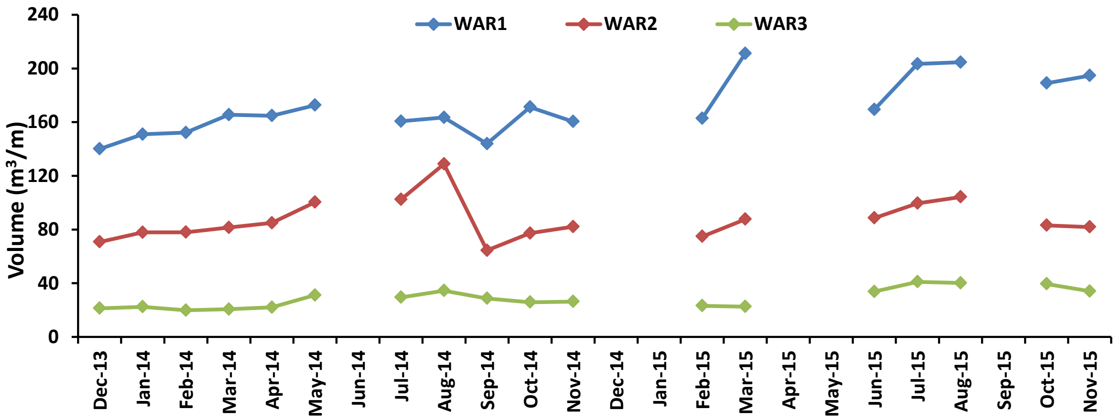

Figure A8.12 Monthly beach profile volume change above 0 m AHD at Warrain Beach between 2013 and 2015

WAR2 followed an accretion phase from 70.7 m^3/m in December/2015 to 128.8 m^3/m in August/2014. A big drop halved the volume in September, and after that volume started to increase again, reaching 82.1 m^3/m in November/2014. In early 2015, volume dropped to 74.8 m^3/m in February and increased to 87.6 m^3/m in March. After two unmonitored months, the volume was 88.6 m^3/m in June/2015, increasing to 104.2 by August/2015. A decrease to 83.1 m^3/m in October, and to 81.9 m^3/m in November happened in thefinal two months of monitoring in 2015.

A volume of 21.3 m^3/m was estimated at WAR3 in December/2013. An increasing trend occurred until May/2014 when volume reached 31.2 m^3/m. The volume was reduced to 29.5 m^3/m in July, but increased again to 34.5 m^3/m in August. A decreasing trend occurred in the final months of 2014 and the initial months of 2015. By March/2015 the volume was reduced to 22.6 m^3/m. Three months later, the volume increased to 33.8 m^3/m, and reached a peak of 41 m^3/m in July/2015. After that, it started to recede and finished off the monitoring period in November/2015 with 34.1 m^3/m.

A trend of accretion could be observed on all profiles at Warrain between 2013 and 2015. WAR2 had minor, WAR3 had moderate and WAR1 had high rates of accretion. WAR1 showed the greatest spread of beach volume (σ= 20.4 m^3/m), followed by WAR2 (σ= 14.7 m^3/m), and WAR3 (σ= 6.9 m^3/m).

The deviations of Warrain beach width at each survey line from the mean are plotted in Figure A8.13. This plot indicates some signs of beach rotation, determined by phase relation, between the northern (WAR1) and the southern (WAR3) profiles. A strong negative phase relation occurred between February and August/2014, and other isolated monitored months such as October/2014 and June/2015. While WAR1 accreted, WAR3 retreated and vice-versa. However, the final four monitored months show no signs of rotation, as both WAR1 and WAR3 accreted. WAR1 showed the greatest spread of beach width (σ= 9.1 m), followed by WAR2 (σ= 7.8 m) and WAR3 (σ= 4.7 m).

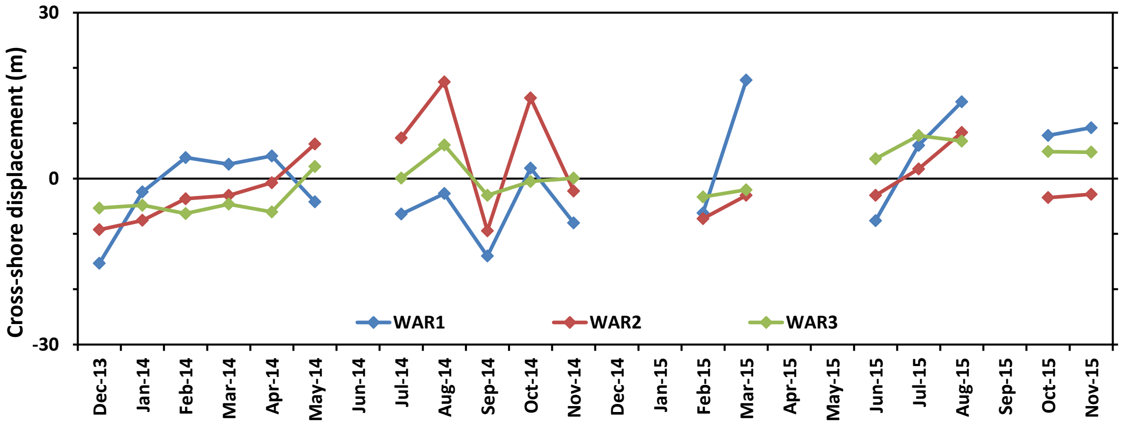

Figure A8.13 Warrain Beach width deviation at each profile line from the mean position

The three beaches studied here have showed no synchronized behaviour in terms of linear trend in shoreline position, direction and magnitude of beach oscillation and rotation, as identified for several other beaches in NSW (Short et al., 2014), suggesting that not necessarily all embayed beaches along the coast behave in a similar manner. These findings need to be reassessed in future in light of a longer monitoring period. Due to the short-term monitoring period, longer term trends of beach behaviour, as well as the establishment of a link with wave climate and the Southern Oscillation Index (SOI), such as the one proposed by Ranasinghe et al. (2004), Short and Trembanis (2004) and Harley et al. (2011), could not be addressed here.

Appendix 9 – SEM images of nearshore sediments

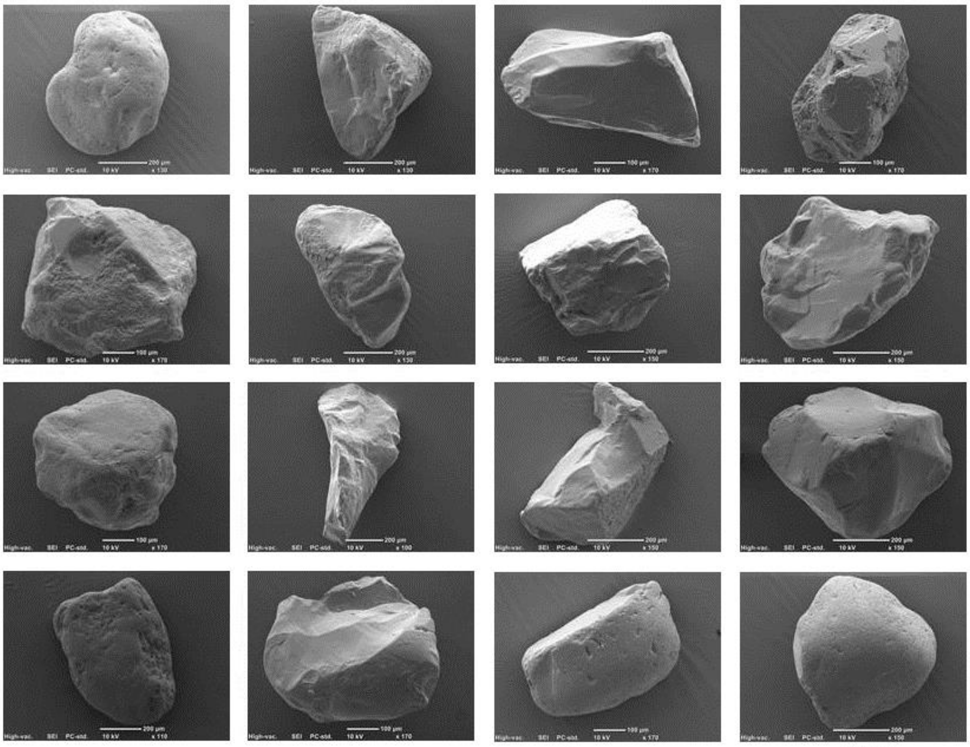

Figure A9.1 SEM images of quartz grains in the 1-2 phi fraction in sample O10, located off Seven Mile Beach. Individual grains varied from angular to sub-rounded and had low to high sphericity.

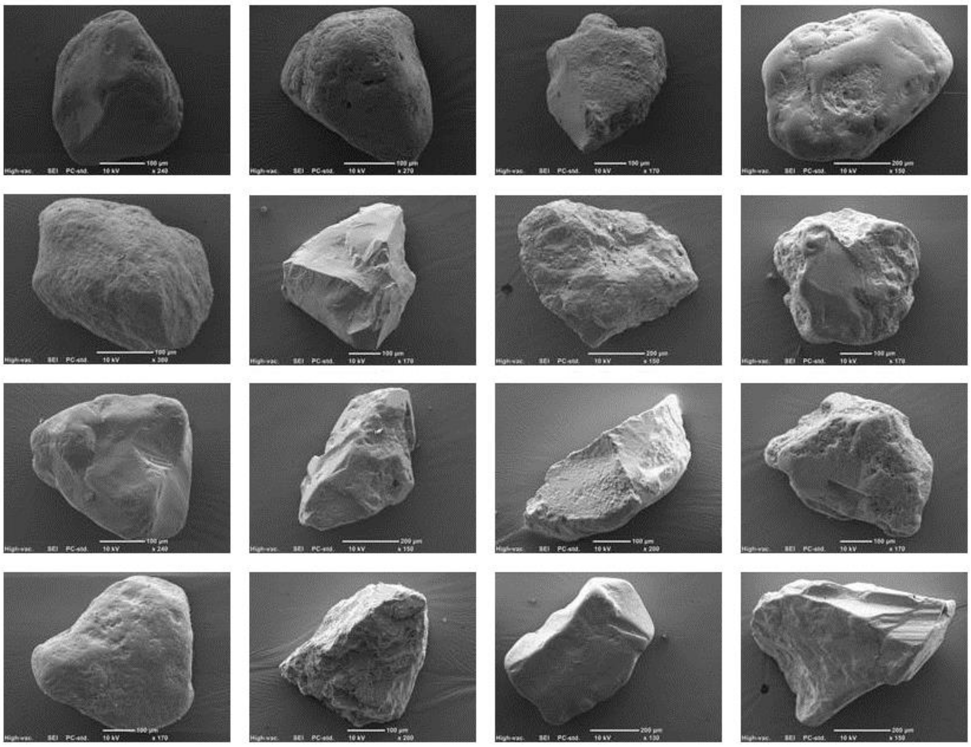

Figure A9.2 SEM images of quartz grains in the 1-2 phi fraction in sample O17, located off Shoalhaven Heads. Individual grains varied from angular to sub-rounded and had low to high sphericity. Most grains were chemically weathered, whereas some had fresh surfaces.

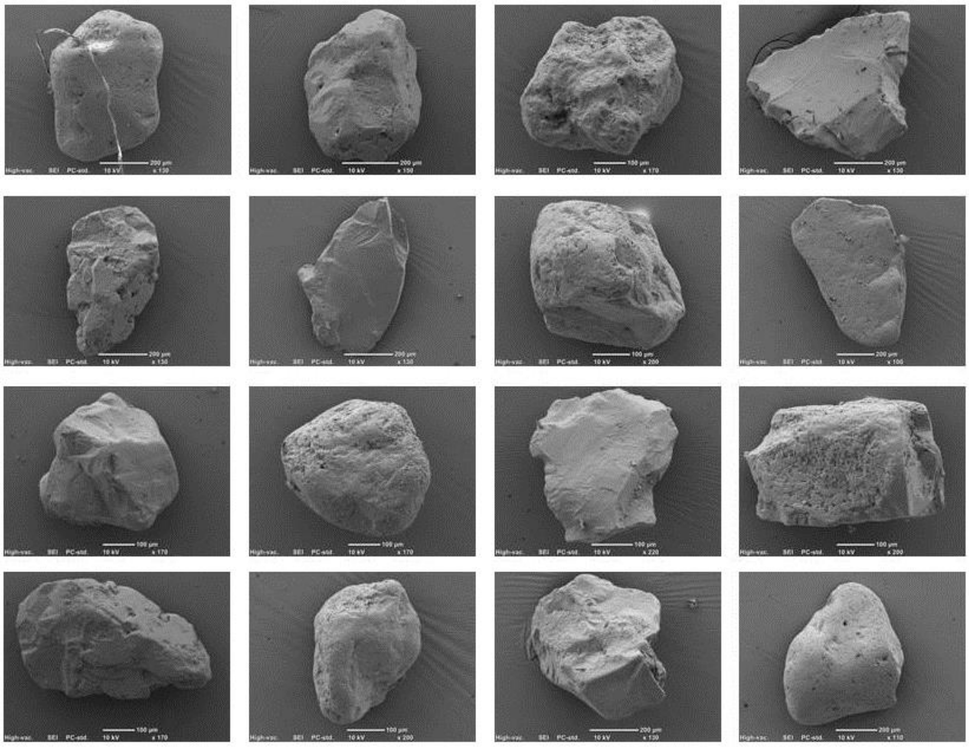

Figure A9.3 SEM images of quartz grains in the 1-2 phi fraction in sample O29, located off Culburra Beach. Individual grains varied from angular to sub-rounded and had low to high sphericity. Fresh surfaces were present in the angular grains.

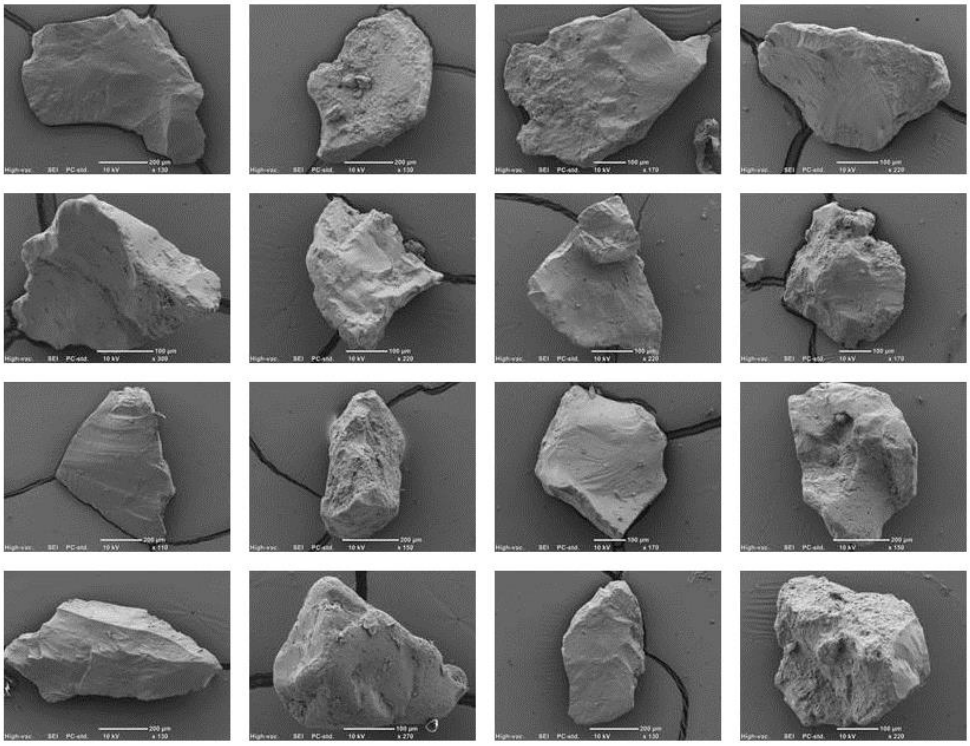

Figure A9.4 SEM images of quartz grains in the 1-2 phi fraction in sample O37, located off Kinghorn Point. Individual grains varied from very angular to sub-angular and had a mix of low and medium sphericity.

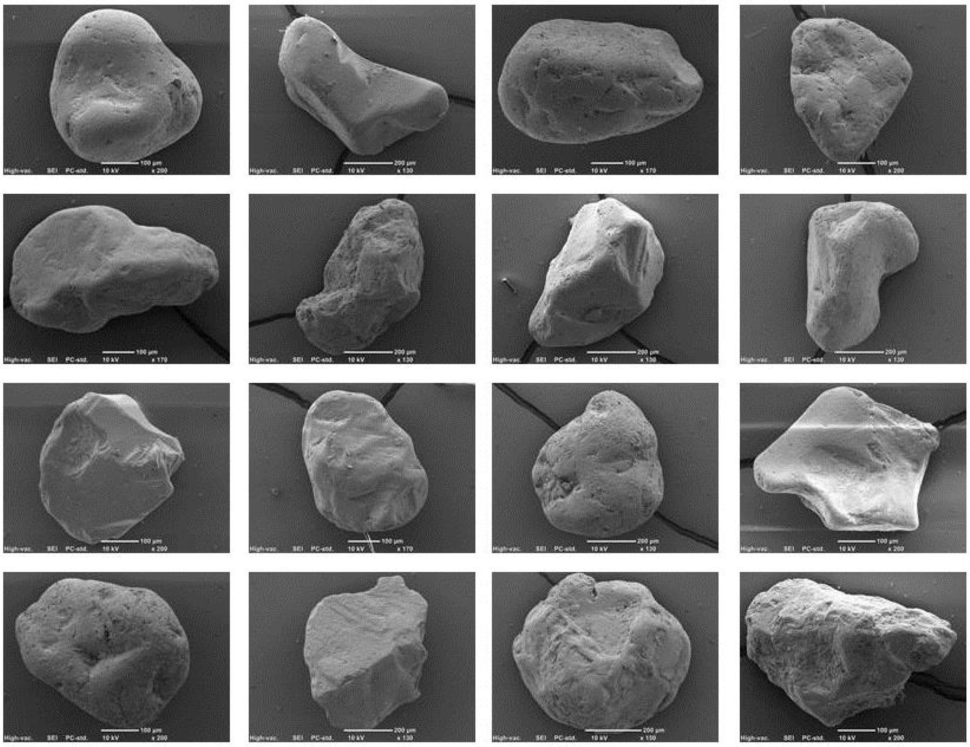

Figure A9.5 SEM images of quartz grains in the 1-2 phi fraction in sample O41, located off Hammerhead Point. Individual grains varied from sub-angular to rounded and had low to high sphericity.